AN INVESTIGATION OF ELECTROCHEMICAL TECHNIQUES
DESIGNED TO MITIGATE THE CORROSION OF STEEL IN
HISTORIC REINFORCED CONCRETE STRUCTURES:
FRANK LLOYD WRIGHT'S FREEMAN HOUSE, HOLLYWOOD, CA
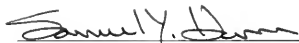
Terry Scott Kreilick

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
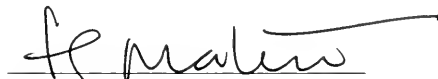Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

2000

Supervisor
Samuel Y. Harris
Adjunct Professor of Architecture

Reader
Jeffrey M. Chusid
Assistant Professor
Director, Historic Preservation Program
School of Architecture
University of Texas at Austin

Graduate Group Chair
Frank G. Matero
Associate Professor of Architecture

Acknowledgments

Table of Contents

List of Illustrations

1.0   Introduction

Steel reinforcing rods, when embedded in high-quality concrete, are normally well protected against corrosion. During solidification of the concrete, a solution of alkali hydroxides and alkaline-earth hydroxides is generated and stored within the gel pores. The pH of this solution is typically between 12 and 14, sufficiently alkaline to pacify the reinforcing steel. When the depth of cover is insufficient or when the quality of the concrete is compromised by carbonation or chloride penetration, corrosion of the steel can occur.

Several electrochemical methods have been developed for the remedial repair of bridge decks and pilings, parking garages, and more recently, residential structures. The methods considered here include cathodic protection, realkalization, and chloride extraction. This thesis explores the applicability of these technologies to the conservation of historic reinforced concrete structures.

The utilization of electrochemical conservation techniques to the Samuel and Harriet Freeman House, a 1924 textile-block house designed by Frank Lloyd Wright, is proposed. The steel-reinforced concrete block system is a failed original technology, but replacement of the concrete textile blocks and the reinforcing rods would be too disruptive and inappropriate. This thesis addresses site-specific conditions which suggest that electrochemical techniques are well suited to the nearly continuous system of reinforcement. Also considered is the applicability of electrochemical conservation techniques to other historic and culturally significant reinforced concrete structures where replacement is not an option.

2.0 Electrochemical Technology

Metal corrodes because it seeks to return to the lower energy state from which it was refined. The natural state of metal is usually an oxide or hydroxide. During the process of corrosion, electricity flows from one metal to another or, when suitable conditions exist, from one part of a metal to another part of the same metal. For corrosion to take place there must be an anode, a cathode, and an electrolyte. An anode is the material (or localized site) where corrosion (oxidation reactions) takes place. A cathode does not corrode, but maintains the ionic balance of the corrosion process (reduction reactions). An electrolyte is a conductive solution containing ions, which are atomic particles or radicals bearing an electrical charge. Charged ions are present in solutions of acids, alkalies, and salts. Water, especially salt water, is an excellent electrolyte.

Current flows from the cathode, through the electrolyte, to the anode causing an oxidation reaction on the surface of the anode. Subsequently, the anode corrodes. The surface of the cathode is subjected to a reduction reaction because the rate of oxidation equals the rate of reduction. Often, hydrogen is generated on the cathode, insulating the cathode from the electrolyte. When this happens, the flow of current stops and the cell is polarized. Some depolarizing agent, like oxygen, is usually present to react with the hydrogen allowing the process to proceed. In iron, the following reactions take place as the corrosion process proceeds[1]:

$$2Fe \text{ (metal)} \rightarrow 2\,Fe^{2+} + 4e^- \text{ (anodic reaction)} \qquad \text{Equation 1}$$
$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \text{ (cathodic reaction)} \qquad \text{Equation 2}$$
$$2Fe^{2+} + 4OH^- \rightarrow 2\,Fe(OH)_2 \text{ (ferrous hydroxide)} \qquad \text{Equation 3}$$
$$2Fe^{3+} + 6OH^- \rightarrow 2\,Fe(OH)_3 \text{ (ferric hydroxide)} \qquad \text{Equation 4}$$
$$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O \text{ (ferric oxide)} \qquad \text{Equation 5}$$

---
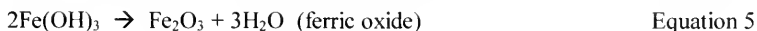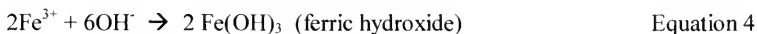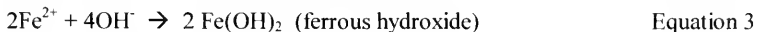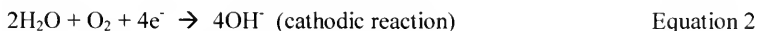
[1] Noel P. Mailvaganam, ed. *Repair and Protection of Concrete Structures*. Boca Raton: CRC Press (1992) p. 146.

An electric current is established when dissimilar metals are in close contact in the presence of an electrolyte. It is the difference in potential that causes this current flow. The "galvanic series" arranges metals by their tendency to corrode. It is this series, shown in Table 1, that designers refer to when selecting compatible metallic materials and, as will be discussed, sacrificial anodes for cathodic protection.

Table 1

Galvanic Series[2]

CORRODED END **(ANODIC)**	Magnesium
	Magnesium alloys
	Zinc
	Aluminum 1100
	Cadmium
	Aluminum2017
	Cast iron
	Chromium-iron (active)
	18-8 chromium-nickel-iron (active)
	Lead-tin solders
	Lead
	Tin
	Nickel (active)
	Inconel (active)
	Hastelloy C (active)
	Brass
	Copper
	Bronze
	Copper-nickel alloys
	Monel
	Silver solder
	Nickel (passive)
	Inconel (passive)
	Chromium-iron (passive)
	18-8 Chromium-nickel-iron (passive)
	Hastelloy C (passive)
	Silver
	Graphite
PROTECTED END	Gold
(CATHODIC)	Platinum

---

[2] Dean M. Berger, "Corrosion Theory." *ASM Metals Handbook, 9th Edition*, Volume 5: Surface Cleaning, Finishing, and Coating. Materials Park: ASM International (1982) p.431.

2.1 Cathodic Protection

Cathodic protection is one method by which steel, copper, lead, and other metals can be protected in corrosive environments. Pitting corrosion can be prevented in passive metals like the stainless steels or aluminum. Cathodic protection can also be used effectively to eliminate stress-corrosion cracking (e.g. of brass, mild steel, stainless steels, magnesium, aluminum), corrosion fatigue of most metals (but not fatigue), intergranular corrosion (e.g. of Duralumin, 18-8 stainless steel), or dezincification of brass.[3] Applications have included offshore structures, pipelines, hot-water tanks, and steel reinforced concrete bridge decks and pilings.

2.1.1 Technology

As applied to reinforced concrete, cathodic protection is an electrochemical technology in which external energy is supplied to the steel surface in the concrete. This process reverses the natural current flow and forces reinforcing steel to function as a current-receiving cathode, thereby controlling corrosion. There are two types of cathodic protection systems for concrete structures: sacrificial and impressed current. Sacrificial systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series, as mentioned above. Sacrificial anode systems involve the direct connection of the anode to the reinforcing steel. No external power

---

[3]   Herbert H. Uhlig and R. Winston Revie, *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering*. New York: John Wiley & Sons (1985) p. 217.

supply is required. Sacrificial anodes for concrete applications include zinc and aluminum-zinc alloys.

Impressed current cathodic protection involves the application of direct current from an inert anode. A power supply (rectifier) is used to impress direct current from the anode, through the concrete, to the reinforcing steel. Typical impressed current anodes include catalyzed titanium, carbon, and zinc. Life expectancy of these systems is typically longer than sacrificial anodes (e.g. >40 years for titanium), however periodic inspections are required to monitor rectifier operation. Figure 1 shows a simplified drawing of an impressed current cathodic protection system, showing the anode wires embedded in slots cut into the concrete.
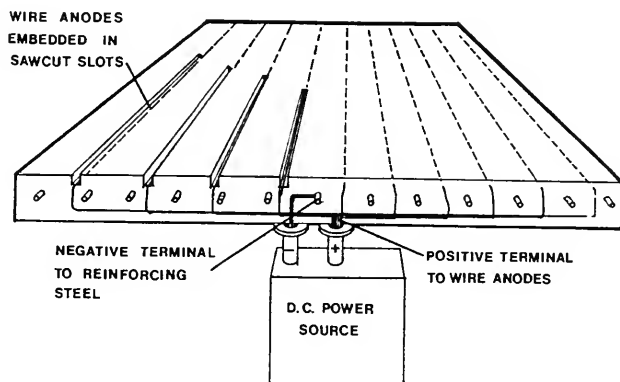
Figure 1
Simplified drawing of an impressed current cathodic protection system. From Kenneth C. Hover, "Cathodic Protection for Reinforced Concrete Structures." *Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures.* Gajanan Sabnis, ed. Pub. SP-85. Detroit: Am. Concrete Inst. (1985) p. 204.

If the concrete is contaminated with chlorides, as the current passes through the concrete, chloride ions will migrate away from the steel surface and hydroxide ions will concentrate near the steel. Mathematical models have been developed to predict the movement of ions through concrete.[4,5] The effects of several variables were examined, including chloride concentration, chloride distribution, pH, current density, and temperature. All of these variables were found to have a significant impact on the chloride/hydroxide ratio at the steel and therefore the corrosive state of the steel. Another model was constructed to predict variations in current density which occur as a result of geometric factors, such as anode resistance, concrete resistance, concrete cover, and steel potential.[6] This model showed that anode resistance could be an important factor in delivering uniform current, with delivered current tending to decay away from the current feed point. This model also underscored the importance of carefully locating embedded reference electrodes in the most anodic areas of the structure.

2.1.2 The Work of Others

In 1824, Sir Humphrey Davy was able to control the corrosion of copper cladding on British warships by attaching blocks of iron to the hulls and using seawater as an

---

[4]   Jack Bennett, "Electrochemical Treatment and Protection: Lessons Learned." *Pacific-Rim-2* (1995).

[5]   Vagelis G. Papadakis, Costas G. Vayenas, and Michael N. Fardis. "Fundamental Modeling and Experimental Investigation of Concrete Carbonation." *ACI Materials Journal* (Jul.-Aug. 1991).

[6]   Bennett, p. 351.

6

electrolyte.[7] By the end of the nineteenth century, sacrificial anodes were being used to protect ship hulls, buoys, and underground structures. Early in the twentieth century, impressed current cathodic protection was also being used to protect underground structures. By 1971, more than a million miles of underground pipeline in the United States utilized cathodic protection.[8] By 1983, government regulations required cathodic protection on all interstate pipelines.[9] Prior to the advent of unleaded fuels and fiberglass storage tanks, many gas stations used a form of cathodic protection for their underground storage tanks.

In the late 1960s and early 1970s it was recognized that concrete could serve as an electrolyte and that it could support a small flow of electricity.[10] It was further recognized that this current could be used to polarize the reinforcing steel in the cathodic direction, and thus mitigate the corrosion process. R.F. Stratfull of the California Department of Transportation was one of the earliest to apply cathodic protection to steel reinforced concrete in bridge decks. [11,12,13] By 1988-89, more than 275 bridge structures in the United States and Canada had been cathodically protected.[14]

---

[7] Sir Humphrey Davy, "On the Corrosion of Copper Sheathing by Sea-Water, and On Methods of Preventing this Effect; and On Their Application to Ships of War and Other Ships." *Philosophical Transactions for 1824*. No. XVI, pgs. 273-280. Read before the Royal Society Jan. 22, 1824.

[8] Kenneth C. Hover, "Cathodic Protection for Reinforced Concrete Structures." *Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures*. Gajanan Sabnis, ed. Publication SP-85. Detroit: American Concrete Institute (1985) p. 178.

[9] ibid.

[10] Bennett, p. 350.

[11] D.L. Spellman and R.F. Stratfull, "Chlorides and Bridge Deck Deterioration," *Highway Research Record*, No. 328, Transportation Research Board, Washington, DC (1970) p. 38-49.

The work of English Heritage at the Inigo Jones gateway of Chiswick House represents one of the first examples of cathodic protection applied to a historic structure.[15] Although not a reinforced concrete structure, a brief review of this work is included to facilitate the discussion on the application of electrochemical methods of treatment to historic structures.

The Inigo Jones gateway was built for Beaufort House (ca. 1621) in Chelsea and, subsequently, moved to Chiswick House, London in 1738 by Richard Boyle, Third Earl of Burlington. The stone of the gatehouse is joined with wrought iron cramps that were corroding and causing the stone to fracture. Previous repairs included the application of a dense, impermeable mortar over the deteriorated stone surface. Removal of the mortar and dismantling of the structure would have resulted in unacceptable loss of original material. Instead, a method of non-destructive electrochemical rehabilitation, impressed current cathodic protection (ICCP), was explored for use on the structure.[16] Work began with trials in 1992 and culminated with full implementation in 1995. Figure 2 shows the Inigo Jones Gateway after the application of the ICCP system.

---

[12]   R.F. Stratfull, "Experimental Cathodic Protection of a Bridge Deck," *Highway Research Record No. 500*, Highway Research Board (1974) p. 1-15.

[13]   R.F. Stratfull, "Cathodic Protection of a Bridge Deck: Preliminary Investigation," *Materials Performance*, Vol. 13, No. 4 (1974) p. 24-5.

[14]   J.P. Broomfield, "Field Survey of Cathodic Protection on North American Bridges," *Corrosion* 31, No. 9 (Sept. 1992).

[15]   Blackney, Keith and Bill Martin. "'Keyhole Surgery' Saves Cramps at Chiswick." *Construction Repair*. (Nov./Dec. 1995) p. 46-47.

[16]   Blackney, Keith and Bill Martin. "The Application of Cathodic Protection to Historic Buildings: Buried Metal Cramp Conservation in the Inigo Jones Gateway, Chiswick House Grounds, London." *Metals*, English Heritage Research Transactions. Volume 1 (April 1998) p. 83-94.

.

A "keyhole" system was developed to provide access to the iron cramps located at a depth of 230 mm. Holes, each 10 mm in diameter, were drilled through the masonry to the cramps. A steel sleeve was placed in the hole and a smaller diameter drill (2.3 mm) used to drill an 8 mm deep hole into each cramp. Plastic-coated wires were soldered onto "banana" plugs and the plugs painted with conductive silver-rich paint. The plugs were then inserted into the steel sleeve and pushed into the iron cramp. The sleeve was then withdrawn leaving the plug and wires in place.

These leads, along with reference electrodes and anodes, were fed to an underground conduit through existing mortar joints or channels cut into repair mortars. The conduit runs approximately 60 meters to Chiswick House where the wires are connected to the power source and monitoring equipment. Continuous monitoring of the cramp's electro-potential can be further refined to include the use of data loggers to record the output voltage and cramp potentials relative to climatic change and consequential masonry wetting and drying cycles.

Figure 2
Inigo Jones Gateway after the application of an impressed current cathodic protection system. Photo from Blackney and Martin, *Metals*, Volume 1 (April 1998) p. 93.

2.2 Realkalization

2.2.1 Technology

Carbonation is a naturally occurring process in which carbon dioxide (CO_2) in the air is absorbed by the calcium hydroxide ($Ca(OH)_2$) found in Portland cement products.[17,18] The result is calcium carbonate ($CaCO_3$) as shown in Equation 6.

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O \qquad \text{Equation 6}$$

While calcium carbonate, in and of itself, does not cause concrete to deteriorate, it does provide suitable conditions for other decay mechanisms to proceed. Calcium carbonate has low solubility in water and tends to seal the pores of the concrete as it advances. In addition, the concrete will be strengthened as the calcium carbonate is formed.[19] The blocked pores will exclude some moisture at the surface and temporarily slow the advance of the carbonation front, but invariably, water will find a path into the structure. This reduced permeability will result in greater retention of moisture and, subsequently, a damp structure. The wet concrete will then serve as an electrolyte, allowing corrosion of steel reinforcement to proceed. In addition, wet concrete will provide a hospitable environment for organic growth.

The carbonation reaction is a transport-controlled mechanism. As such, the progress of the carbonation front depends on the porosity and permeability of the concrete, the existence of cracks, and the conditions of the exposure. The rate at which

---

[17]   J. Mietz and B. Isecke, "Investigations on Electrochemical Realkalization for Carbonated Concrete." Paper No. 297, *Proceedings of Corrosion 94*. Houston: NACE International, 1994.

[18]   Mailvaganam, p. 162.

[19]   ibid, p. 163.

the carbon dioxide advances is strongly influenced by the relative humidity of exposure.[20] A relative humidity of 40 to 70 % appears to be optimal for rapid penetration, while the rate is much slower for relative humidities less than 30% and greater than 75%. Good quality dense concrete carbonates very slowly. Penetration of only 5-10 mm after 50 years of exposure is possible. A low strength, permeable concrete, however, may carbonate to a depth of 25 mm in less than 10 years.[21]

In concrete without steel reinforcement, the effect of carbonation is not an issue. There is no loss to the compressive strength of the concrete and no reinforcement to corrode. In steel reinforced concrete structures, however, carbonation will eventually affect the steel. When the carbonation front reaches the reinforcing steel the passivation provided by the highly alkaline calcium hydroxide is lost and the steel will start to corrode in the presence of oxygen and moisture.

The method of electrochemical realkalization was developed to restore alkalinity to carbonated concrete.[22,23] Vector Construction Ltd., of Winnipeg, Manitoba, is the licensed North American representative of the Norcure®[24] realkalization process patented by Øystein Vennesland and John Miller in Norway. The technique involves passing a current through the concrete to the reinforcement by means of an anode mesh attached to the exterior surface of the concrete. The anodic mesh material is usually steel or platinized titanium. The anode is placed in an electrolytic reservoir to conduct electricity and to provide alkalis to the carbonated concrete. The electrolyte is most often a solution of

---

[20]   ibid, p. 163.

[21]   ibid, p. 163 and Philip H. Perkins, *Repair, Protection, and Waterproofing of Concrete Structures*. New York: Elsevier (1986) p. 37.

[22]   Mailvaganam, p. 379.

[23]   Mietz, p. 3.

[24]   Norcure is a registered trademark of Fosroc International Limited, Oslo, Norway.

sodium carbonate. The electrode outside the concrete and the reinforcement inside acting as cathode are connected to a direct current source. Figure 3 illustrates the process.
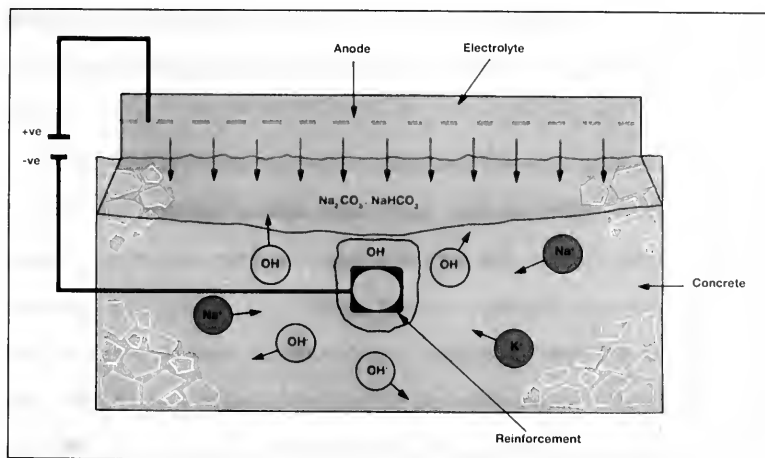
Figure 3
Schematic illustration of the realkalization process. An alkaline
sodium carbonate electrolyte is transported into the concrete, increasing the
alkalinity of the cover zone. At the same time, electrolysis at the reinforcement
surface produces a high pH environment, which repassifies the steel.
Illustration courtesy of Vector Construction Ltd.

Prior to treatment, the concrete should be characterized to determine the extent of carbonation. The location of the carbonation front should be recorded for future documentation of the effect of realkalization. Concrete surface coatings should be removed prior to realkalization since coatings may increase the treatment time or limit the efficacy of the treatment. If for any reason the removal of a surface finish must be avoided, a realkalization trial should be conducted to establish necessary treatment time.

Realkalization can be performed under all weather conditions as long as the electrolyte does not freeze. Realkalization is suitable for most types of reinforced concrete. Pre-stressed, post-tensioned structures, and concrete with unusual

characteristics may require some modification of the technique. The number of rebar connections required depends on rebar continuity. There should be at least one connection for each 50 m^2 of concrete. The continuity is determined by means of resistance measurements performed prior to or during installation. The resistance between two rebar connection points should be less than 1 ohm, but up to 10 ohms is generally acceptable.[25]

During realkalization, the anodic reaction is forced to take place on the anode mesh, while the cathodic reaction takes place over the entire reinforcement surface. Immediately, all reinforcement corrosion is stopped and, during treatment, all corrosion sites become deactivated by the cathodic reaction. Realkalization is complete once the level of pH is raised to about 12. The pH level subsequently stabilizes around 10.5, which is sufficiently alkaline to maintain passivity of the reinforcement. The alkaline electrolyte penetrating from the surface into the concrete pores prevents more significant decreases of the pH. The reaction between sodium carbonate and carbon dioxide proceeds according to Equation 7.

$$Na_2CO_3 + CO_2 + H_2O \rightarrow 2NaHCO_3 \qquad \text{Equation 7}$$
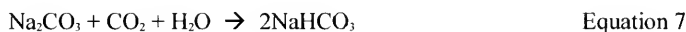
In the state of equilibrium with a constant carbon dioxide concentration of the atmosphere only small amounts of sodium carbonate will react to form sodium hydrogen carbonate and hence future carbonation leads only to a slight decrease of pH. In this way, the ingress of sodium carbonate into the concrete pores should act as a carbon dioxide trap. The dominant transport mechanism may vary, but electro-osmosis and migration of ions are the two main contributors. Simultaneously, electrolysis at the surface of the reinforcement produces a very alkaline environment.

---

[25]   Vector Construction Ltd. "Non-Destructive Electrochemical Treatment to Halt Ongoing and Prevent Future Reinforcement Corrosion in Carbonated Concrete." Undated Technical Paper.

The time required for treatment varies between 3 and 14 days. The current density applied during treatment also varies, between 0.8 and 2 A/m^2. In cases where electro-osmosis cannot be used, a variation of the treatment allows realkalization by electrolysis alone. This situation may arise when carbonated concrete is also chloride contaminated, or if certain surface coatings or impregnations of the concrete have been used.[26]

The reservoir, which keeps the electrolyte in contact with the concrete surface and the mesh anode, may be a sprayed-on cellulose fiber, felt cloth, or coffer tanks.[27] Cellulose fiber, saturated with the electrolyte, is sprayed directly onto the concrete surface. Prior to spraying, wooden battens are attached to the concrete surface using plastic plugs. The anode mesh is attached to the wooden battens, which act as spacers between the concrete and the mesh. The cellulose fiber and the electrolyte are sprayed on to ensure electrolytic continuity between the anode mesh and the concrete surface. Fiber is applied to a thickness that encapsulates the mesh. Its adhesion properties make cellulose fiber suitable for most concrete surfaces, but it is primarily used for vertical surfaces. It has the advantages of being able to conform to any concrete shape, it is self-adherent, and it is not expensive. Disadvantages include the need to keep it wet during the treatment process, and the clean up and disposal of the used material at the end of the project. Depending on the type used, cellulose fiber can provide some buffering and it generally provides greater spacing between the anode and the concrete surface.

Synthetic felt mats, like sprayed cellulose fiber, are inexpensive, but from a practical standpoint, they are limited to horizontal surfaces.[28] The felt cloth is rolled onto the concrete surface in two layers, with the anode mesh placed between them. Depending on the application, the felt mats may be rolled up and re-used on future projects. The felt mats must also be kept wet during the treatment process.

---

[26]   ibid.

[27]   ibid.

[28]   ibid.

Surface mounted, coffer tanks can be built to fit a given structure or built in panels to cover a larger area. The initial cost is high, but if they can be re-used many times, the cost per usage can be reduced.[29] The tanks may consist of plastic sheets with sealing edge strips of compressible expanded plastic and built-in anode mesh. They are fastened directly to the concrete surface and filled with electrolyte. Tanks do not require frequent "topping off" as long as evaporation and leakage are minimized.

The power supply is an AC/DC rectifier that may be either current or voltage controlled.[30] The leads from the rebar are connected to the negative pole and the leads from the anode mesh are connected to the positive pole of the rectifier. The power supply is then switched on and adujusted to give a current density of ideally 1 A/m² of concrete surface. During treatment, the anode system must be kept moist. After a few days of treatment, samples are taken at previously marked test locations. Phenolphthalein may be used to indicate, qualitativily, change in pH. The treatment continues until satisfactory realkalization is achieved. At that time, all leads are disconnected and the anode system removed. The surface is washed with water and remaining cavities and test holes repaired. Reference electrodes are often installed to monitor the stability of the treated concrete.

2.2.2 The Work of Others

In the ten years since its introduction, realkalization has been applied to over 200 structures, primarily in northern Europe.[31] Information provided by Vector Construction Ltd. indicates the following:

---

[29]   ibid.

[30]   ibid.

[31]   "Norcure List of References per March 1996," from Vector Construction Ltd. The number of projects includes nineteen demonstration projects, for which no area of treatment was reported.

Table 2

Realkalization Projects Utilizing the Norcure Process

Year	Number of Projects	Area Treated (m^2)
1987	1	400
1988	7	1,560
1989	10	3,661
1990	7	20,542
1991	22	19,647
1992	20	23,719
1993	40	30,679
1994	43	27,842
1995	47	35,712
1996 (through March)	4	5,474
	201	169,236

The realkalization of a 13 story building at the Technical University of Trondheim, Norway was undertaken during the summer of 1989 by Malermester Jacob Opdal Overflateteknikk A/S.[32] The steel reinforcement on the main facades, which consists of rows of slender columns filled out with windows and concrete plate elements, exhibited signs of corrosion. The depth of carbonation was determined to be about 20 mm. The realkalization of about 2000 m^2 was performed at 12 V DC and was completed in 3 to 5 days. The current density was approximately 0.3 to 0.5 A/m^2. Twelve reference electrodes were installed to monitor future corrosion. A second 13 story building at the University was treated in the summer of 1993. The surface area treated on the second building was about 3000 m^2.

---

[32]   Vector Construction Ltd., "Realkalization: Report 1 - Technical University, Trondheim, Norway," http://www.norcure.com/13.htm

The Hoover Factory Building in London, built in 1932, underwent realkalization treatment in 1992.[33] The Art Deco building, designed by Wallis Gilbert & Partners, was designated a Grade II building in 1990. Grade II listing requires that any alteration to the structure be approved by the governmental agency, English Heritage. The three key areas to be restored were the faience, the windows, and the concrete. The concrete was in poor condition with extensive corrosion of the reinforcing steel. The depth of carbonation was up to 70 mm, with an average depth of 30 mm. Replacement of the concrete was unacceptable to English Heritage.

Realkalization treatment was performed by MAKERS Industrial Ltd. Areas of up to 400 m^2 were treated at one time. A total of 4500 m^2 were treated in 23 weeks, with an average treatment time of 4 days. The effect of the treatment was monitored on-site using the pH indicator phenolphthalein. After treatment, the alkaline fiber mixture was removed, anode mesh, and leads dismantled, and the surface washed with high pressure water. After drying, a cementitious skim coat was applied to the surface, followed by an elastomeric coating.

In 1993, a survey of two 10 story apartment buildings in Blindernvein, Oslo, Norway, revealed extensive carbonation and reinforcement corrosion.[34] A conventional break-out and repair method was advised in the spring of 1995. After removing the paint by light grit blasting, however, it became apparent that far more extensive corrosion of the steel had occurred. It was estimated that five or six times more concrete would be need to be replaced than originally considered. Constructed in 1958, the buildings had undergone conventional repairs in 1970 and in the mid-1980s. The previous work was not successful for two reasons: 1) a failure to determine the full extent of areas requiring repair, and 2) an incomplete understanding of the mechanisms of concrete deterioration.

---

33   Vector Construction Ltd., Realkalization Report 2 - "Hoover Building in London,"
        http://www.norecure.com/hoover.htm

34   Vector Construction Ltd., Realkalization Article - "Blindernveien: a realkalisation case study,"
        http://www.norecure.com/art2.htm

Subsequent repairs incorporated realkalization of the carbonated concrete. Full continuity of the reinforcement was established to facilitate the realkalization process and cracked and spalled concrete was patched. The anode system utilized consisted of a steel mesh embedded in an alkaline reservoir temporarily applied on the surface of the concrete. The mesh was fixed to the vertical faces using plastic plugs and spacers. On the balcony soffits, the mesh was fixed to wooden battens fastened to the concrete. When the mesh was in place, specially formulated cellulose fiber was sprayed directly onto the concrete surface together with a liquid electrolyte.

Treatment proceeded in 500 m^2 sections requiring three workers for 3-4 days. Leads to the reinforcing steel were connected to the negative pole of an AC/DC rectifier. Leads to the anode mesh were connected to the positive pole. A voltage was applied and adjusted to give a current flow equivalent to approximately 1 A/m of concrete surface. The rectifiers automatically adjusted the voltage to maintain the required current output.

Concrete cores were obtained and examined on-site using the pH indicator phenolphthalein to determine when carbonated concrete was sufficiently realkalized. Voltage and current flow were checked once or twice a day and fresh electrolyte sprayed onto the fiber reservoir when necessary. Once the treatment was complete, the rectifier was switched off, the cables disconnected, and the anode system removed. The concrete surfaces were washed with high pressure warm water and left to dry before applying a protective coating.

2.3   Chloride Extraction

2.3.1   Technology

The electrochemical removal of chloride from concrete structures is accomplished by applying an anode and an electrolyte to the external concrete surface, and passing direct current between this anode and the reinforcing steel, which acts as a cathode. Since anions (negatively charged ions) migrate toward the anode, it is possible to migrate chloride ions toward the anode and out of the structure. The chloride content of the concrete is thereby reduced, particularly on and around the negatively charged reinforcing steel. The concrete, for all practical purposes, becomes free of chlorides. Simultaneously, the electrolytic production of hydroxyl ions at the reinforcing steel surface results in a high pH being generated around the steel. When the process is terminated and the anode and electrolyte removed the reinforcing steel will be situated in chloride-free, highly alkaline concrete. The process of chloride extraction is shown schematically in Figure 4.

The amount of chloride that can be removed depends on the chloride concentration, chloride distribution, current, and total applied charge. If all of the current was carried by chloride ions, then each ampere-hour of charge would remove 1.32 grams of chloride. The efficiency of this technique is approximately 10-20%, resulting in the removal of about 40-60% of the chloride.[35] The duration of a typical treatment is 6 to 8 weeks at a current density of about 100 mA/ft² (compared to cathodic protection which operates at approximately 1 mA/ft²).[36]

---

[35]   Bennett (1995), p. 346.

[36]   ibid.
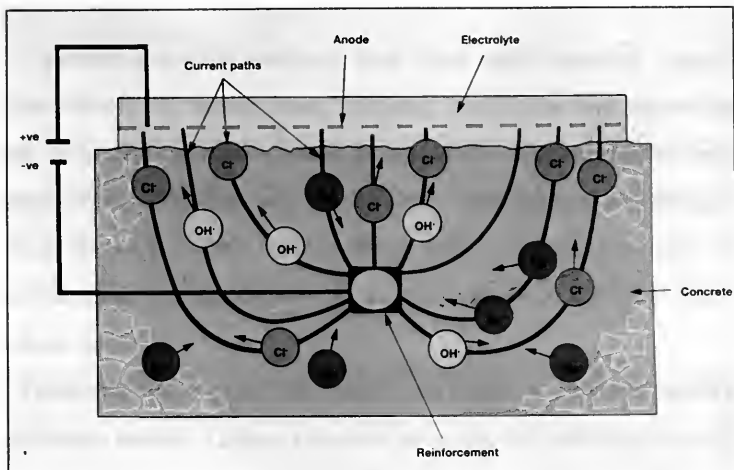
Figure 4
Schematic illustration of the chloride extraction process. An electric field is temporarily applied between the reinforcement in the concrete and an externally mounted anode mesh, transporting chloride ions out of the concrete.
Illustration courtesy of Vector Construction Ltd.

The proper selection of the anode, electrolyte, and the electrolyte media is paramount to assuring a successful treatment. The two most common anodes are catalyzed titanium mesh and steel mesh. Catalyzed titanium mesh has the advantage of being an inert anode which, under suitable conditions, does not corrode. The catalyzed coating on the mesh is consumed over time. After one or two uses this coating is significantly deteriorated. Titanium mesh may require the use of a buffered electrolyte or regular electrolyte replacement since chlorides will concentrate in the electrolyte resulting in the acidification of the electrolyte over time. The cost of titanium mesh is approximately six times the cost of steel mesh. Steel mesh is not inert and is consumed during the operation of the system. By the completion of the treatment a large percentage of the steel mesh will be reduced to rust. This rust will stain the surface of the concrete during treatment and, depending on the application, may be of some concern.

Numerous electrolyte solutions have been used, including water, calcium hydroxide solution, and "lithium borate" solution. Water is the most efficient electrolyte available. It is inexpensive and available at most sites. No environmental protection or containment is required when using potable water. The greatest disadvantage of using water as an electrolyte is that it has no buffering ability. If water is used as an electrolyte with an inert anode in a closed system, electrolyte acidification will occur if the water is not replaced regularly.

Calcium hydroxide electrolyte solutions can be used to provide a limited buffering capability where desired. Calcium hydroxide has a very low solubility in water, but if a reservoir of solid calcium hydroxide is maintained this material will slowly dissolve over time to replace the spent solution. Calcium hydroxide solutions are more expensive than water, require time to prepare and maintain, and are less efficient.

The term "lithium borate" is commonly used to refer to an electrolyte containing a mixture of lithium hydroxide and boric acid. This electrolyte provides a highly buffered solution suitable for some closed system applications. Lithium based electrolytes have been specified for work where concrete is suffering from alkali-silica reactivity (ASR). Lithium has been shown to be effective in mitigating ASR. Disadvantages of lithium electrolyte solutions include their relatively high cost and the need for recirculating systems to minimize the volume of electrolyte required.

Electrolyte media for chloride extraction are identical to materials used for realkalization, described above. They suspend, hold, or contain the electrolyte solution on the surface of the concrete and provide separation between the anode and the concrete surface. The three types of electrolyte media presently in use are: 1) sprayed cellulose fiber; 2) synthetic felt mats; and 3) surface mounted tanks.

2.3.2   The Work of Others

The first experiments on the electrochemical removal of chloride from concrete were conducted in the United States by D.R. Lankard, et. al. and G.L. Morrison, et. al. in the mid-1970s.[37,38]   Very high voltages were applied for a short period of time.   This heated the concrete and caused other undesirable effects resulting in the discontinuation of the work.   In the late-1980s, the process was reconsidered by Norwegian Concrete Technologies (NCT).   The first trial project in North America was completed for the Ontario Ministry of Transportation on a portion of the substructure of the Burlington Skyway.   This effort was part of the Strategic Highway Research Program (SHRP) of the National Research Council, jointly funded by the United States and Canada.

The SHRP conducted additional field validation trials between the fall of 1991 and fall of 1992.[39]   Chloride removal was conducted on an Ohio bridge deck, and bridge substructures in Florida, New York, and Ontario.   Active corrosion was occurring on a substantial portion of each treated structure, and chloride contamination was well above threshold levels.   Damage due to corrosion, however, was not very extensive.   Based on earlier laboratory work the researchers decided to conduct the field tests at a current less than 500 mA/ft^2 and voltage less than 50 volts.   It was also decided to maintain pH of the electrolyte neutral or basic to prevent etching of the concrete surface and evolution of chlorine gas.

The first field trial was conducted on an Ohio bridge deck in the fall of 1991. Chloride contamination was high and active corrosion was occurring, but physical

---

[37]   Lankard, D.R., et. al. *Neutralization of Chloride in Concrete*. Battelle Columbus Laboratories, FHWA Report No. FHWA-RD-76-6 (September 1975).

[38]   Morrison, G.L., et. al. *Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis*. Kansas Department of Transportation, FHWA Report No. FHWA-KS-82-2 (August 1982).

[39]   Bennett (undated), p.2.

deterioration had not yet begun. The treatment was conducted by constructing a pond on the horizontal surface of the deck, and placing an inert catalyzed titanium anode in the pond together with a sodium borate buffer electrolyte. Current density for this trial was low because cold temperatures and very resistive concrete, and treatment time was long (61 days). Chloride analyses of the pond indicated that about 33 pounds of chloride (equivalent to 54 pounds of NaCl) was removed during the treatment at a current efficiency of about 20%. Problems encountered include overflow of the pond due to excessive rainfall and vandalism.

The second field trial was conducted in the spring of 1992 on pilings underneath the B.B. McCormick bridge near Jacksonville, Florida. Chloride content in the concrete was high in the splash and tidal zone and active corrosion was evident. A prefabricated anode/blanket composite was strapped on each pile from three feet above high tide to five feet below high tide. Seawater was used as the electrolyte, and was continuously circulated from the intracoastal waterway to the top of the chloride removal system. From there the electrolyte flowed by gravity back to the waterway. The system operated for 18 days at an average current density of 0.33 A/ft^2, accumulating a total charge of 135 A-hr/ft^2. The success of this trial was difficult to judge. Although steel in the treatment area was strongly polarized and chloride was certainly removed, the exact efficiency and amount of chloride removed could not be determined. Measurements indicated that a significant amount of current was leaking to seawater.

The third field trial was conducted on the substructure of a bridge in Albany, New York in June 1992. This structure was suffering more distress than previous trials, with about 15% of the treated area delaminating and requiring patching. Chloride concentrations and corrosion rates were high. Here again, prefabricated anode/blanket composites were strapped on the columns and electrolyte continuously circulated throughout the system. In this case, however, a captive sodium borate buffer electrolyte was used. Measurements and observations indicated localized high current densities,

probably a result of the inhomogeneous nature of the structure. Current densities ranged from 0.1 to 0.3 A/ft², and two zones accumulated 80 and 93 A-hr/ft² in 17 and 24 days respectively. Based on concrete analyses, chloride removed was 10-17 pounds (16-28 pounds as NaCl), at a current efficiency of 7.3 to 12.7 percent. It was felt that these figures were low. Problems at this site included difficulty in sealing electrolyte on two columns, and electrolyte dilutions due to rainwater runoff.

The fourth field trial was conducted on abutments of a bridge over the Montreal River in Latchford, Ontario, in August 1992. The trial was interesting since the structure contained alkali sensitive aggregate. This condition would ordinarily preclude electrochemical chloride removal on this structure, since the process has been determined to aggravate ASR. A 0.2 molar lithium borate buffered electrolyte was used, however, and lithium ion was injected into the concrete during treatment. This practice has been found to prevent damage due to ASR. An anode/blanket composite was installed on each abutment corner and electrolyte continuously circulated through the system. The system operated 23 days at an average current density of 0.16 A/ft², accumulating 84 and 89 A-hr/ft² of charge on two zones. Post treatment analyses showed that 4.0 and 2.45 pounds of chloride (total of 10.6 pounds as NaCl) had been removed from the two zones respectively at current efficiencies of 18.7 and 11.7 percent. Petrographic analysis of the concrete showed that the treatment had no adverse effect on the alkali-silica reaction occurring in the structure. The main problem encountered was again electrolyte dilution due to excessive rainwater runoff.

To date, approximately 2 million square feet of concrete have been treated on about 50 projects in the United States, Canada, Norway, Sweden, England, Japan, Switzerland, Italy, and Germany.

3.0   The Freeman House

Frank Lloyd Wright, designed the house at 1962 Glencoe Way in Hollywood, California early in 1924, for Samuel and Harriet Freeman. The Freeman House is one of four textile-block structures designed by Wright in his attempt to enter the expanding housing market of southern California. The Storrer, Ennis, and Freeman houses, and their immediate predecessor La Miniatura, mark Wright's transition from the Prairie style and the Arts and Crafts to the Modern Movement. Wright turned to the concrete block as his fundamental building unit in the southwest.

The concrete block system envisioned by Wright was inexpensive and did not require highly skilled labor during construction. The block was to be easily produced, on-site, of indigenous materials. The material and the system of construction were to reflect the nature of the place and the traditional methods of construction in the southwest. In addition, the system had to be resilient to survive the seismic activity of the area.

In Wright's words, less than ten years later:

> The concrete block? The cheapest (and ugliest) thing in the building world. It lived mostly in the architectural gutter as an imitation of "rock face" stone.
> Why not see what could be done with that gutter-rat? Steel wedded to it cast inside the joints and the block itself brought into some broad, practical scheme of general treatment then why would it not be fit for a phase of modern architecture? It might be permanent, noble, beautiful. It would be cheap.
> There should be many phases of architecture as modern.
> All that imagination needed to make such a scheme feasible was a plastic medium where steel would enter into inert mass as a tensile strength. Concrete was the inert mass and would take compression. Concrete is a plastic material - susceptible to the impress of imagination. I saw a kind of weaving coming out of it. Why not weave a kind of building? Then I saw the "shell." Shells with steel inlaid in them. Or steel for warp and masonry units for "woof" in the weaving. For block-size - say manhandled units weighing 40 to 50 pounds - all such units or blocks for weaving or shells to be set steel-wound and steel-bound. Floors, ceilings, walls all the same - all to be hollow.

I had used the block in some such textured way in the Midway Garden upper walls. If I could eliminate the mortar joint I could make the whole fabric mechanical. I could do away with skilled labor. I believed I could and began on "La Miniatura."

Lightness and strength. Steel the spider, now spinning a web within the plastic material to be wedded to it by inner core of cement.

Hollow wall-shells for living in! The "shell," as human habitation. Why not?

Another phase of the concept of architecture as organic and yet the same.

The straight line, the flat plane, now textured, the sense of interior space coming through the openings all to be woven as integral features into the shell. The rich encrustation of the shells visible as mass, the true mass of the architecture. Here, a legitimate feature of construction.[40]

La Miniatura, designed and built for Alice Millard, utilized concrete block construction, as suggested in Wright's reminisce, but it did not incorporate steel reinforcing rods and it was laid on conventional mortar beds.[41] Interlocking flanges along the edges of the blocks provided rigidity. Steel reinforcement was incorporated in the three later structures.

The Freeman House is the smallest of the textile-block houses, encompassing approximately 2,500 square feet. The lot, totaling about 7,000 square feet, is situated on a steep incline. The front facade is on the north and faces a small, winding residential street (Figure 5). The south facade terminates the axis of Highland Avenue (Figure 6). The building permit was issued on April 8, 1924 and a notice of completion filed on March 23, 1925. The Freeman House, now owned by the University of Southern California, is listed on the National Register of Historic Places and is a City of Los Angeles Cultural Monument.

---

[40] Frank Lloyd Wright, *An Autobiography*, p. 235-6.

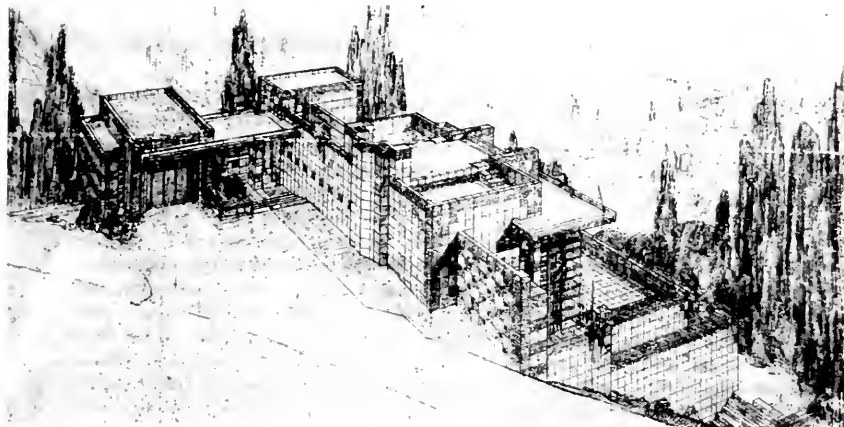Figure 5
Original rendering of the north facade
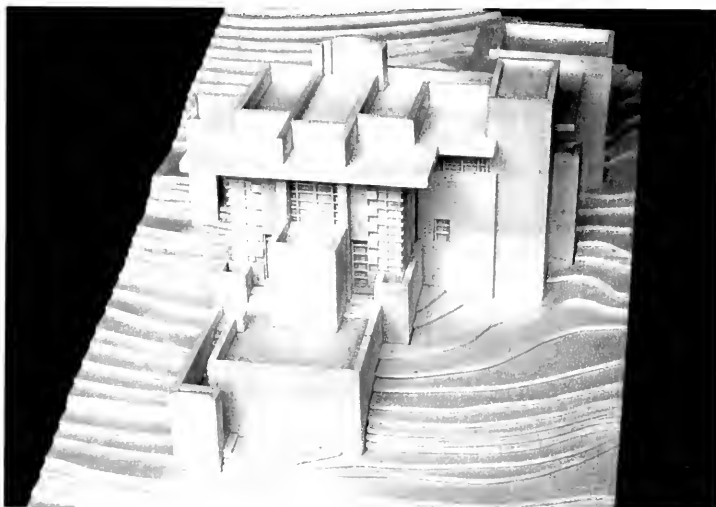of the Freeman House, looking southeast.

Figure 6
Model of the Freeman House, looking north.

---

[41] Neil Levine, *The Architecture of Frank Lloyd Wright*, p. 154.

3.1   Construction Methodology

All pre-cast slabs or blocks shall be made of clean sand or other suitable aggregate and Portland Cement, in the proportions of one of cement to four of sand, thoroughly mixed in a mechanical mixer to the consistency that will stand up when squeezed by the hand. All slabs or blocks will be formed under pressure in metal molds and not allowed to dry within a period of ten days from the time they are made. All blocks shall be perfect, free from cracks or defects of any kind. The slabs and blocks will be set into the wall as indicated in Fig. 1 and Fig. 4, with 1/4" rods between them, horizontally and vertically, the joints are then to be grouted full with Portland Cement, one of cement to three of clean, sharp sand. The joints shall be carefully filled solid in every case, the blocks being saturated with water before the pouring is done. The outer shell and inner shell to be the same. The two shells shall be tied together across the air-spaces by 1/4" steel rods hooked at vertical rods at every intersection of every joint and the rods asphalted or covered with a thickness of Portland Cement mortar- equivalent to 2" in thickness. Where the joists or rafters rest upon the walls they shall extend through the air spaces to the inside of the outer blocks and rest upon a continuous plate. Where the rafters rest the connecting rods between the course against which they rest shall be turned over and stapled to them securely.[42]

The above quotation is from the "Owner's Copy" of the construction specifications. The standard cast concrete block used in the construction of the Freeman House was 16 by 16 by 3 1/2 inches thick. Figure 7 shows an isometric view of a patterned block and a cross-section. At least 44 different variations of the standard block were used. Each edge of the block has a concave, semicircular channel to receive a steel reinforcing rod. It is estimated that more than 9000 reinforced vertical blocks were used in the construction of the Freeman House.

Figure 8 shows the molds found in the Freeman House garage after Harriet Freeman's death in 1986. The basic mold is a cast aluminum flask with machined faces. It is four-sided and measures 17 7/8 by 17 7/8 by 4 7/8 inches. The bottom is a tin plate and is shaped to form a coffer on the back-side of the block. The top is cast-aluminum with a

---

[42]   From the "Owner's Copy" of the legal documents, consisting of an Architect's Contract, Agreement between Contractor and Owner, Receipt and Specifications. Reproduced in Jeffrey Mark Chusid, Historic Structure Report: Samuel and Harriet Freeman House (July 1989).

plain or patterned machined face. The flask is hinged at three corners. The fourth corner

has a latch. There is a convex rib that forms the channel on the perimeter of the block.
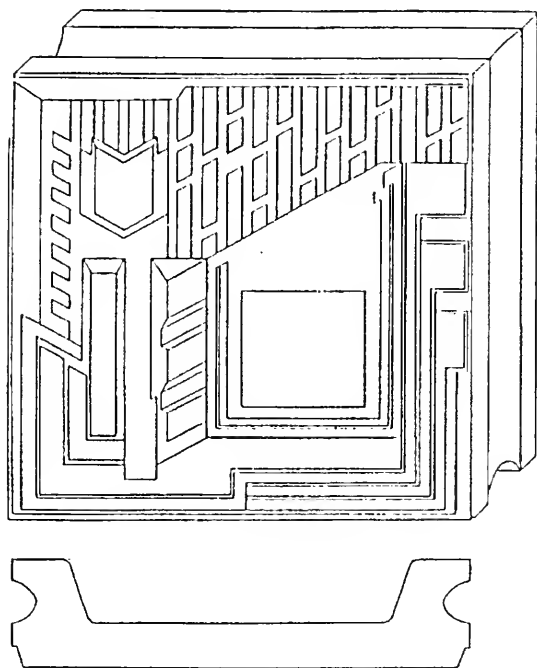
Figure 7
Isometric view of a patterned block and a cross-section.

Figure 8
Cast concrete block production mold.
Photograph courtesy of the Freeman House.

The textile blocks were fabricated on a 4' by 6'iron-top table set up on the hillside west of the house. Sand and cement was mixed (4 to 1) dry twice in a wooden box with a hoe. Just enough water was added so that the material held its shape. The form was filled with a shovel full of mix and the top wiped off with a stick. The top plate was put in place, followed by a 2 x 4 on top of the form. The 2 x 4 was struck several times with a 6

lb. sledge. The finished block was then removed from the form and was supposed to be watered 2 or 3 times every day for 21 days. There would always be 2 or 3 rows of blocks drying in the sun.

The blocks were set without a bedding mortar. In theory, this would simplify the construction process and result in a structure able to flex during seismic activity. A double wythe was utilized in the construction of the house to provide an insulating air space. The blocks were set in place by sliding them between two vertical reinforcing rods. Figure 9 are schematic drawings of textile block construction from Frank Lloyd Wright's invention disclosure. Figures 10 and 11 show the Freeman House during construction.

When a row of blocks was in place, a horizontal reinforcing rod was laid in the channel created along the top of the blocks. When several rows were stacked, a loose grout was poured down the vertical channels. The grout was supposed to fill both the vertical and the horizontal channels, encapsulating the reinforcing rod. In practice, however, the grout did not flow throughout the network of channels. The grout stopped about one-third of the way in many of the horizontal sections, leaving the center third unfilled. The flow may have been retarded by the build-up of trapped air. In addition, the horizontal rods positioned at the bottom of the channel were not uniformly encapsulated. The reinforcement in the vertical channels often lacked coverage due to overlapping rod and inter-wythe ties.

As the blocks were stacked, the two wythes were tied together with smooth steel rod looped around the reinforcing rod. The ties were not encapsulated in grout. Figures 12 and 13 show examples of the ties that connect the wythes.
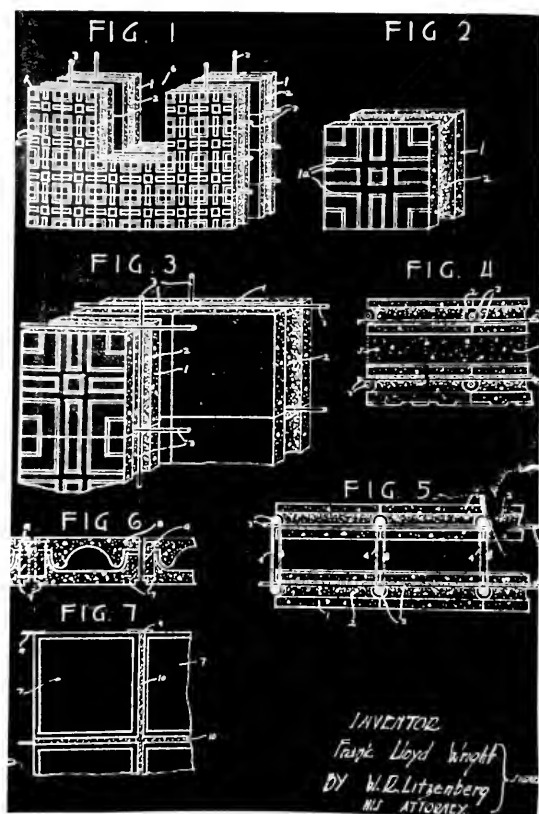
Figure 9
Schematic drawings of textile block construction
from Frank Lloyd Wright's invention disclosure.

Figure 10
Freeman House construction photo showing placement
of vertical reinforcing rod. Courtesy of the Freeman House.

Figure 11
Freeman House construction photo showing placement
of vertical reinforcing rod. Courtesy of the Freeman House.

Figure 12
Tie-rod connecting inner and outer wythe.
Photograph courtesy of K. Fong.

Figure 13
Tie-rod connecting inner and outer wythe.

3.2   Present Condition

The concrete blocks of the Freeman House have deteriorated to varying degrees, depending on their exposure, the presence of localized conditions, seismic activity, and other factors. This, and the variety of block types used in the construction, will make the task of conservation challenging. All blocks will not need to be treated.

The blocks on the south and east exterior elevations have weathered the most. The blocks on the east exhibit more structural failures than any other elevation. This is due primarily to the fact that this is the largest of the facades, stretching from the garage on the north to the slumber terrace on the south. This elevation is also the least commonly seen as it abuts the property line and faces downhill. The steepness of the slope has exacerbated the failures along this elevation.

The Freeman House "faces" south. It is this elevation that contains the most dramatic features of the house. As a whole, the textile blocks on the south are the most deteriorated of any on the structure. Exposure to sun, acid rain, and smog have eroded much of the detail on the patterned textile blocks. There are more exposed corners on this elevation. To form a corner, the edges of the adjoining blocks were mitered. The mitered corners are prone to failure due to inadequate structural support.

The west façade appears to relatively sheltered by its proximity to the house next door. This elevation does not extend the same distance as that on the east. The textile blocks are in good condition compared to the rest of the house.

The north elevations include those of the garage, storeroom, and the main house. The north elevation of the main house rises to meet the remnants of a parapet at the roof

35

level. A substantial portion of the parapet has collapsed. This façade, which stretches from the street to the main entrance to the house, includes several cracked blocks. There are few patterned blocks on this wall. They outline the east and west sides and the upper border. The seven patterned blocks along the upper border are perforated and serve as windows along an interior hallway. The textile blocks at the base of this section are often wet.

Deterioration of the blocks generally takes one of four forms: 1) large losses due to fractures in the concrete; 2) loss of detail primarily due to erosion of the surface; 3) discoloration of the concrete surfaces due to soiling and efflorescence; and 4) chemical and physical failure of the block due to poor construction practice and choice of materials.

Much of the cracking observed has occurred within a few inches of a vertical or horizontal joint and runs roughly parallel to the joint. When these parallel cracks occur along all four edges simultaneously in a single block, the resulting fracture is referred to as a "ring fracture." A ring fracture is the result of internal stresses that develop as the reinforcing rods expand due to corrosion. The stresses are transmitted through the grout and into the block itself. A second type of cracking is observed in close proximity to many of the mitered corners and run roughly 45 degrees of the joints. Figures 14 through 18 illustrate ring fracture and the general condition of the exterior block. Loss of detail has occurred only on the exterior weathered faces of the blocks. Efflorescence was observed on the interior, but not the exterior.

An appropriate mortar is usually softer than the masonry units it binds. For the construction of the Freeman House, the grout specification called for 1:3 cement to sand. This is relatively hard when compared to the blocks. The blocks, as mentioned previously,

were 1:4 cement to sand. In this way, the grout used at the Freeman House may provide columnar support to the continuous vertical and horizontal joints of the stack bond.

While greater rigidity of the structure may have been achieved, the lean 1:4 ratio of cement to sand yielded extremely weak and porous blocks. The cement content was insufficient to bond all of the aggregate. The blocks are, therefore, more susceptible to deterioration due to weathering, water infiltration, and accelerated carbonation.
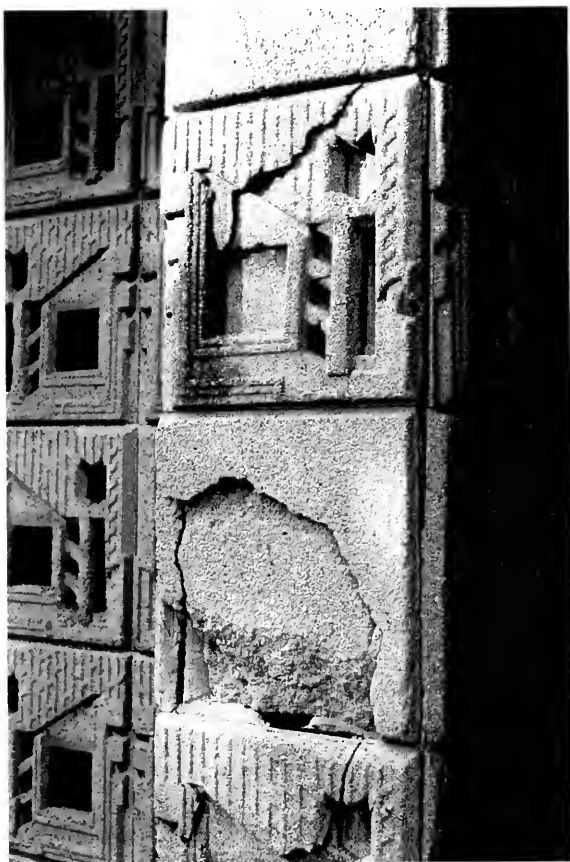

Figure 14
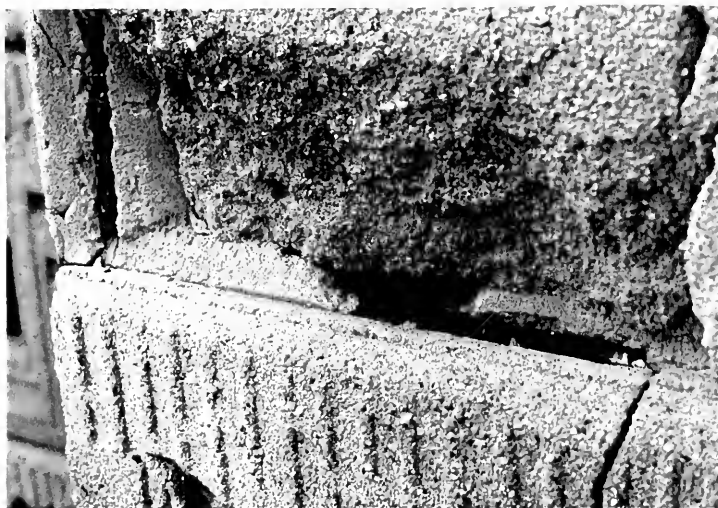Ring fracture of concrete block on south facade.

Figure 15
Detail of ring fracture of concrete block on south facade.

Figure 16
Detail of ring fractured corner block on the south facade.
Two vertical reinforcing rods are visible.

.

Figure 17
Ring fracture of concrete block on south facade.

Figure 18
Detail of the intersection of four concrete blocks on the south facade.

3.3   Materials Characterization

In an effort to further understand the deterioration of the concrete at the Freeman House, samples were taken of the concrete and the reinforcing steel for optical and electron microscopic analysis. The primary constituents of the concrete were determined using x-ray diffraction techniques and thin-section petrography. The microstructure of the reinforcing rod was characterized by metallographic analysis.

3.3.1   Concrete

Samples of the Freeman House concrete were collected during a site visit in January 1997. The samples were prepared for analysis at the Architectural Conservation Laboratory (ACL) and the Laboratory for Research on the Structure of Matter (LRSM) at the University of Pennsylvania by a variety of techniques.

Small bulk samples (5-6 grams) were sputter coated with gold prior to examination in a JEOL JSM 6400 scanning electron microscope (SEM). The SEM has an energy dispersive spectroscopic (EDS) analyzer to determine the chemical composition of materials in a semi-quantitative manner. Figures 19 through 26 are representative SEM micrographs, and their respective EDS spectra, of the aggregate and cement of the concrete.

Two thin sections of the concrete were prepared; one was stained to identify any potassium feldspar that might be present. Petrographic analysis was performed using two different polarizing microscopes (Olympus BX40 and Zeiss Axiophot). Photographs were

taken at magnifications of 25X and 100X to illustrate features of interest. Cross-polarized and plane-polarized light was used.

Analysis of the thin-sections indicates that the aggregate consists primarily of quartz, amphiboles (hornblende), and biotite. These minerals constitute approximately 80% of the cross-section. A very fine matrix of cementious materials account for the remaining 20%. Figures 27-34 are micrographs of the thin-sections.

To determine the composition of the fine cementious matrix, a sample of the concrete was ground using a mortar and pestle. The ground sample was suspended in acetone, applied to a glass slide, and allowed to dry thoroughly. The samples were then subjected to x-rays using a Rigaku X-ray Powder Diffractometer. The initial and final 2-theta were 5 and 60, respectively. The scan speed was 2.

The raw data was then subjected to micro-powder diffraction search/match (μPDSM) software to identify the constituents of the sample. The software incorporates the *Powder Diffraction File* provided by the International Centre for Diffraction Data (JCPDS). The primary constituents were identified as silicon oxide (quartz: SiO_2), sodium calcium aluminum silicate (albite: $NaAlSi_3O_8$), and calcium carbonate (calcite: $CaCO_3$).

Carbonation of the concrete was confirmed by subjecting a bulk sample to a 1% solution of phenolphthalein in ethyl alcohol. Phenolphthalein is colorless in a neutral (up to pH 8.5) or acidic environment. Above pH 8.5, phenolphthalein is reddish-pink in color. As described in Section 2.2, when the calcium hydroxide in Portland cement absorbs carbon dioxide it is converted to calcium carbonate. Calcium carbonate is almost neutral. Phenolphthalein can, therefore, be used to monitor the depletion of the more highly

alkaline calcium hydroxide. When phenolphthalein is applied to concrete from the Freeman House no color change is noted, indicating full carbonation.
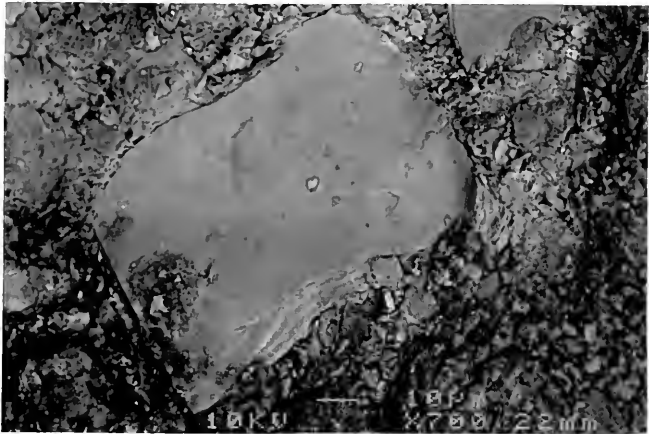
Figure 19
SEM (backscatter) micrograph of aggregate
in concrete block. (700x magnification)
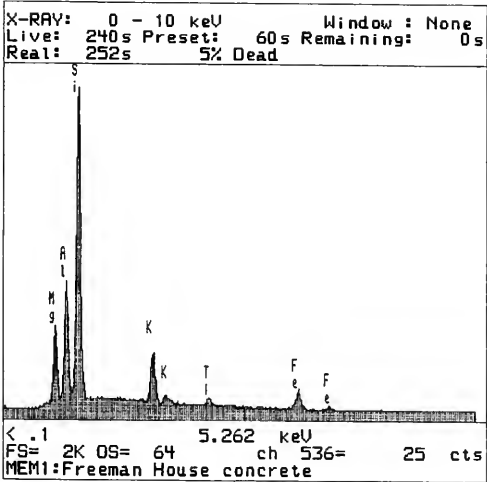
Figure 20
EDS spectra of aggregate shown in Figure 19.
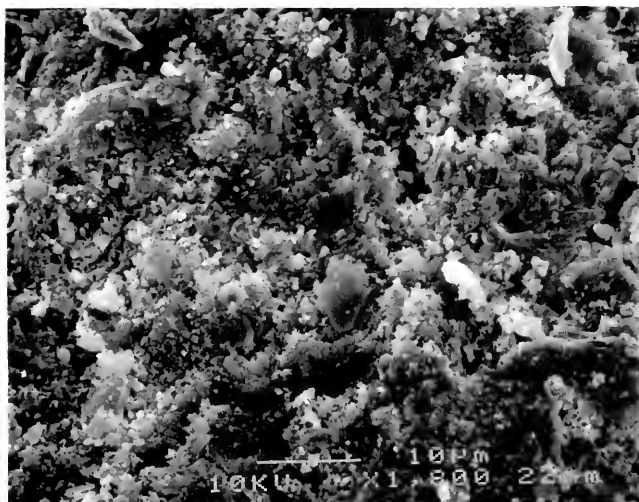
Figure 21
SEM micrograph of concrete matrix. (1,800x magnification)
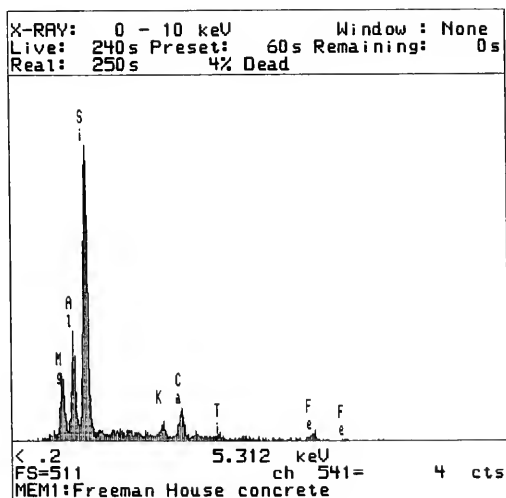
Figure 22
EDS spectra of concrete matrix shown in Figure 21.
Spectra is for entire field of view.
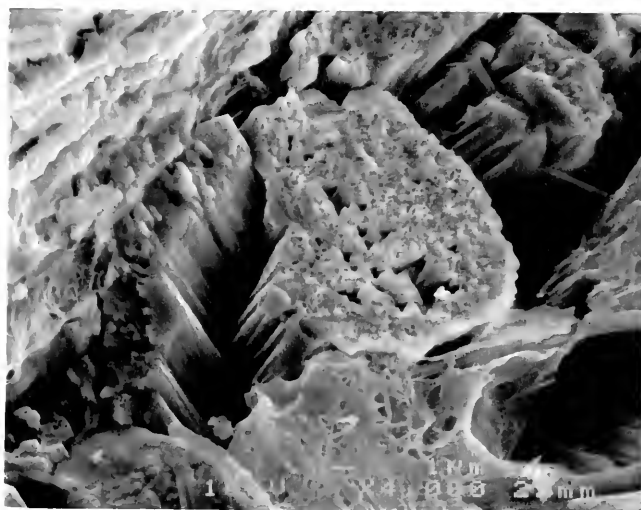
Figure 23
SEM micrograph of Portland cement, primarily calcium silicate, from Freeman House concrete. Cleavage, as shown, was frequently observed in this sample. (4,000x magnification)
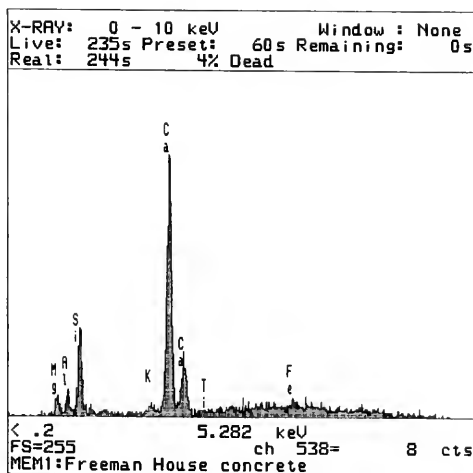
Figure 24
EDS spectra of Portland cement shown in Figure 23.
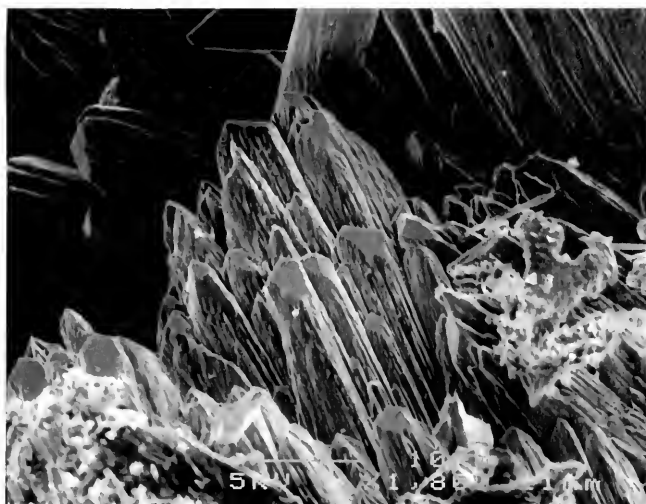
Figure 25
SEM micrograph of nearly pure calcium crystals in
Freeman House concrete. (1,800x magnification)


```
X-RAY:    0 - 10 keV          Window : None
Live:    60s Preset:    60s Remaining:    0s
Real:    64s       6% Dead
```
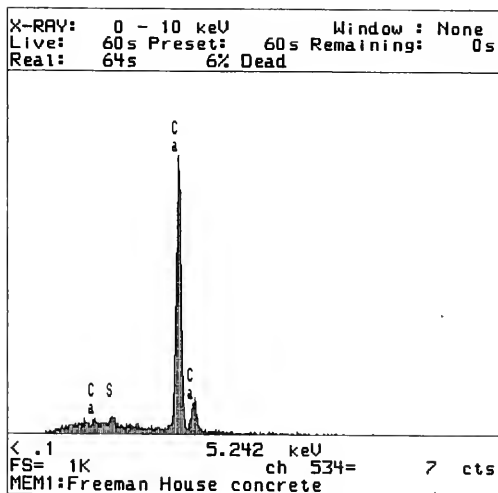
Figure 26
EDS spectra of calcium crystals shown in Figure 25.
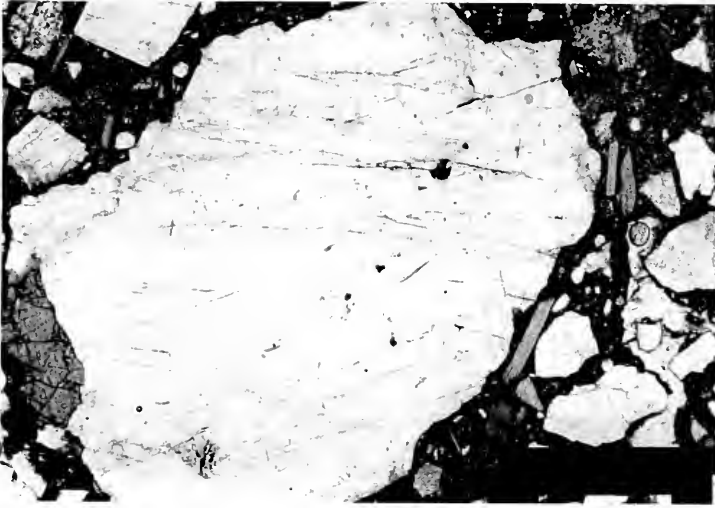
Figure 27
Optical micrograph of petrographic thin-section of Freeman House concrete.
Overall view in plane-polarized light showing a large quartz crystal in the center,
green amphiboles, and yellow biotite. These aggregates constitute approximately
80% of the section. The very fine matrix constitutes the remaining 20%.
(25x magnification)
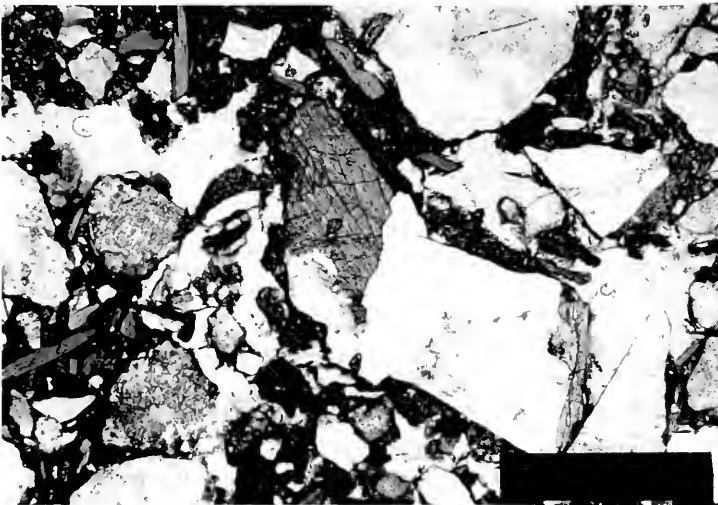
Figure 28
Optical micrograph of petrographic thin-section of Freeman House concrete.
Overall view with polars crossed. (25x magnification)
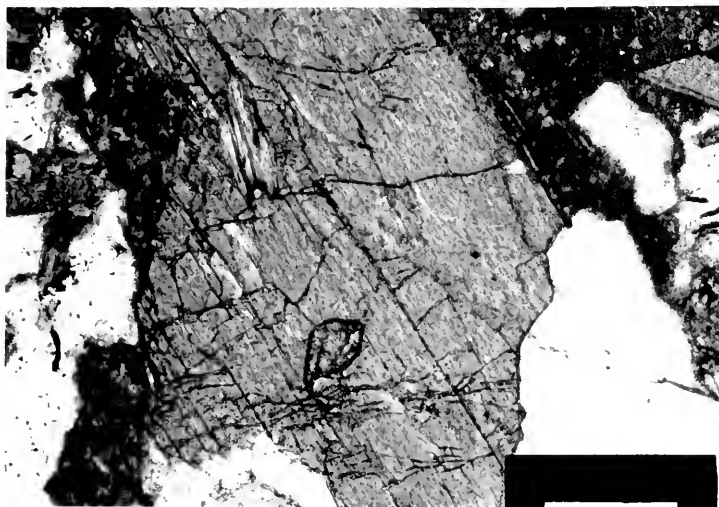
Figure 29
Optical micrograph of petrographic thin-section of Freeman House concrete
showing the cleavage of an amphibole. (plane-polars, 100x magnification)
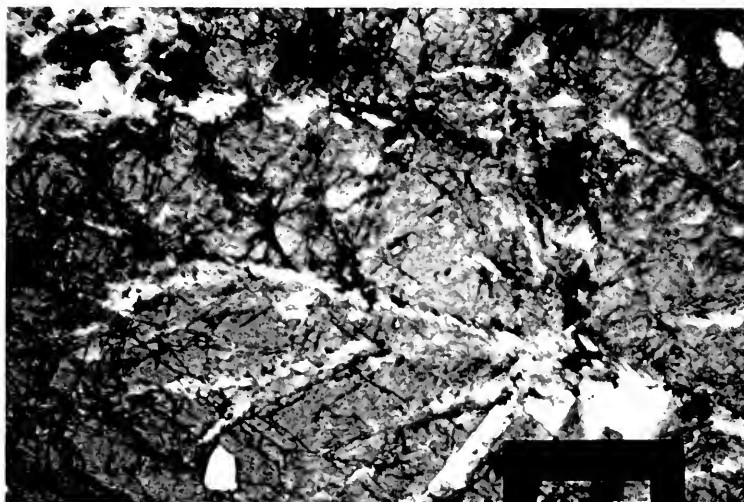
Figure 30
Optical micrograph of petrographic thin-section of Freeman House concrete
showing a very large amphibole altered by the oxidation of iron.
This deterioration is observed after long exposure to water.
(plane-polars, 100x magnification)
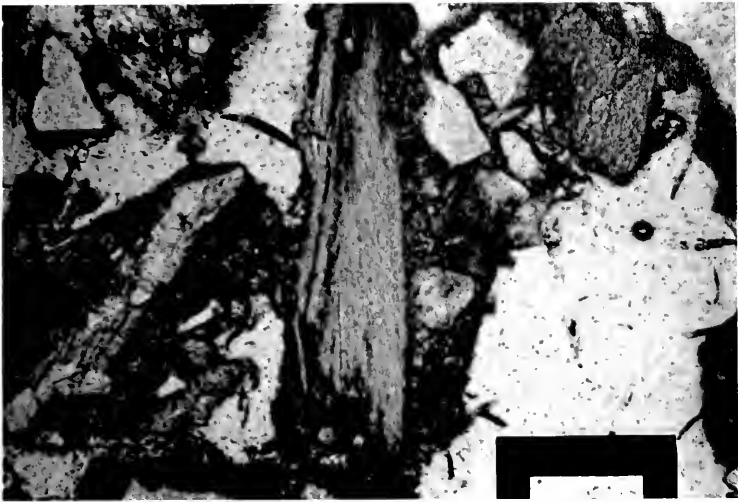
Figure 31
Optical micrograph of petrographic thin-section of Freeman House concrete
showing biotite (mica) with a minimum absorption of light.
(plane-polars, 100x magnification)
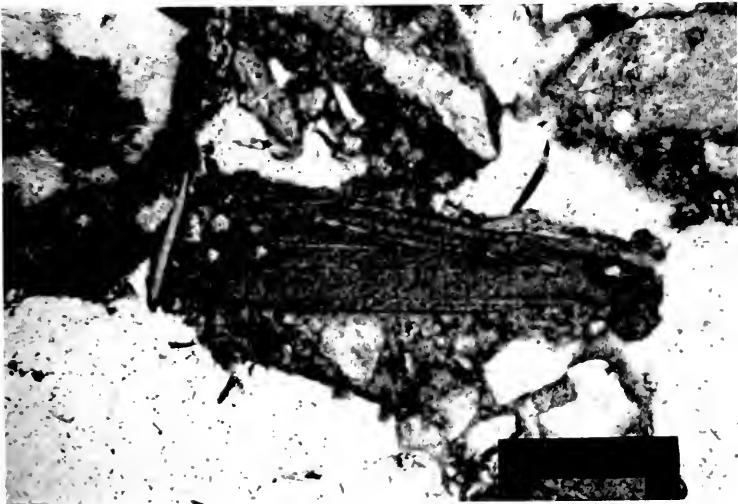
Figure 32
Optical micrograph of petrographic thin-section of Freeman House concrete
showing biotite (mica) rotated 90 degrees to illustrate maximum
absorption of light. (plane-polars, 100x magnification)
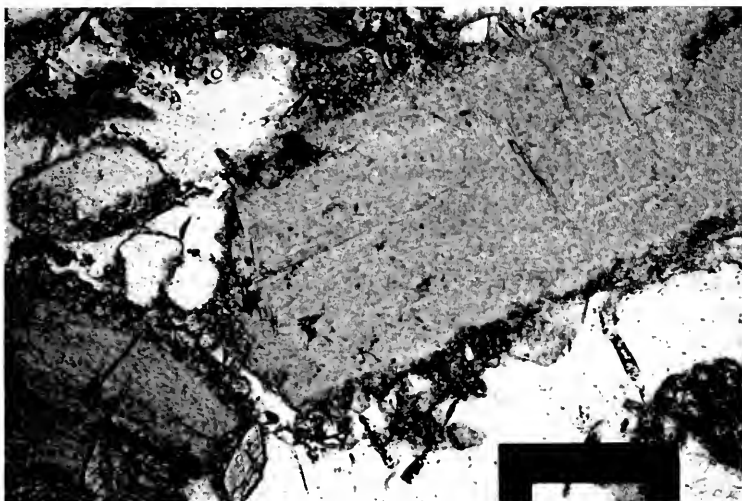
Figure 33
Optical micrograph of petrographic thin-section of Freeman House concrete
showing yellow-stained potassium feldspar. (plane-polars, 100x magnification)
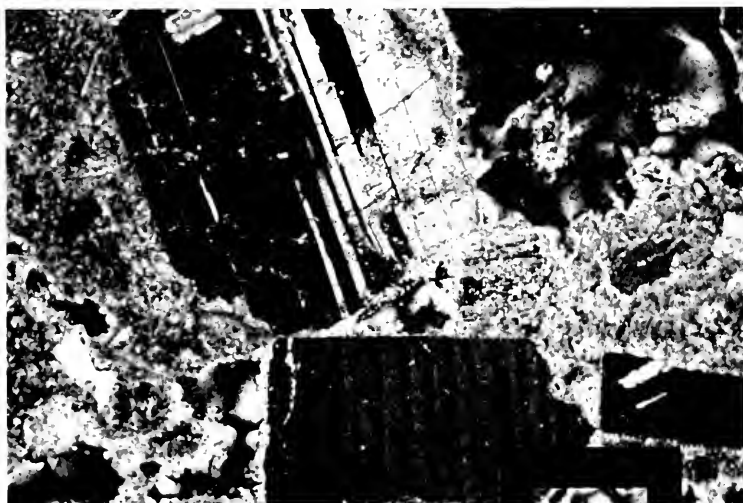
Figure 34
Optical micrograph of petrographic thin-section of Freeman House concrete
showing the lamellar twinning of plagioclase feldspar.
(crossed-polars, 100x magnification)

3.3.2 Steel Reinforcing Rod

The steel reinforcing rod of the Freeman House is nominally 0.26" by 0.26" square. The rod has deformation ridges that run perpendicular to the length of the rod and are spaced every half inch. The chemical composition of the 1030 reinforcing rod was determined using spectrochemical analysis conducted as per ASTM E415.[43] The analysis yielded:

Carbon	0.28%	Nickel	0.09%
Manganese	0.65%	Molybdenum	0.02%
Silicon	0.29%	Copper	0.21%
Phosphorus	0.007%	Vanadium	0.01%
Sulfur	0.025%	Carbon	0.41%
Chromium	0.11%		

The same report indicates that the tensile and yield strengths of an uncorroded sample were determined to be 63,000 psi and 47,800 psi, respectively. Elongation in 1" was determined to be 37%. Much of the reinforcing rod that is visible, however, is corroded to varying degrees. A brief examination does not yield a consistent pattern of deterioration. In some areas, the reinforcing rod has lost more than 50% of its cross-sectional area. Figure 35 is an SEM micrograph showing the iron oxides on the surface of one section of reinforcing rod.

Transverse and longitudinal samples of the reinforcing rod were prepared for metallographic examination. The samples were cut using an Isomet saw with diamond

---

[43]   Nabih Youseff & Associates. *Freeman House, Hollywood, California: Architectural/Engineering Evaluation.* (14 Sept. 1995).

wafering blades. The samples were then mounted in a thermosetting epoxy and polished with a series of abrasive grit papers of decreasing coarseness. Figure 36 shows a portion of the reinforcing rod in longitudinal section. Inclusions in the reinforcing rod indicate the directionality of the metal caused by hot-rolling during fabrication.

The polished cross-sections were then slightly etched with a solution of 2% nital in ethanol. Nital is a widely used etchant for carbon and alloy steels, containing 1-3% HNO_3 in ethanol or methanol. Etching reveals the microstructure by enhancing the contrast between pearlite and ferrite in the metal. The samples were then examined using a Nikon metallographic microscope. Figures 37-40 are representative micrographs of the longitudinal and transverse cross-sections.

Examination of the polished and etched cross-sections indicate that the steel was hot rolled. The microstructure is pearlite plus ferrite, with approximately 0.2% carbon. The grain size, as determined according to ASTM Standard Method E112, is 10 at a magnification of 100x.[44]

The analyses of the reinforcing rod indicates that the steel is inherently sound. It is susceptible, however, to long term exposure to water and water-borne corrosive agents. Once the protective environment of the highly alkaline concrete is compromised, the steel will deteriorate.

---

[44]   American Society for Testing and Materials. Standard No. E112-85: Standard Methods for Determining the Average Grain Size. Volume 03.03: Metallography; Nondestructive Testing. *Annual Book of ASTM Standards.* Philadelphia: ASTM (1986) p. 115-148.
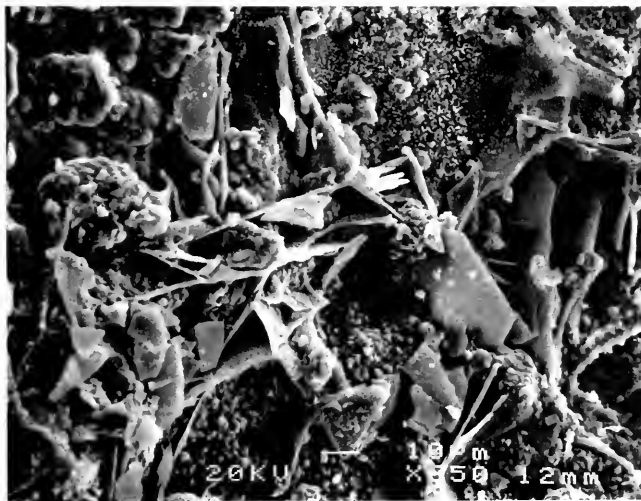
Figure 35
SEM micrograph of iron oxide on the surface of steel
reinforcing rod from Freeman House. (650x magnification)

Figure 36
Optical micrograph of Freeman House rebar shown in a longitudinal section
showing typical inclusions. (unetched @ 600x magnification)
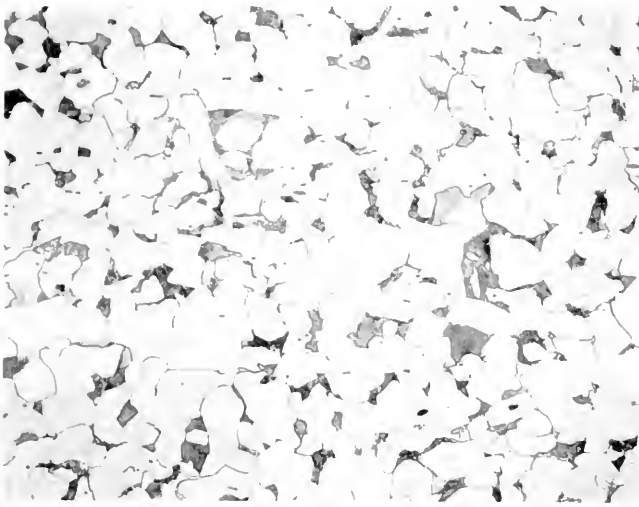
Figure 37
Optical micrograph of Freeman House rebar shown in a longitudinal section.
The hot-rolled structure is pearlite plus ferrite, with approximately 0.2% carbon.
(2% nital etch @ 600x magnification)
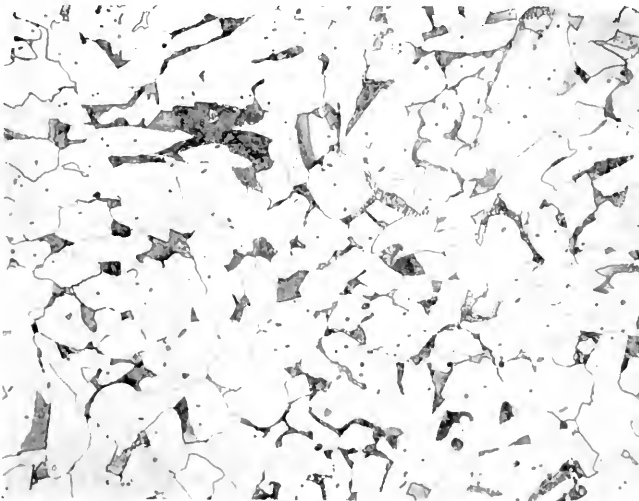
Figure 38
Optical micrograph of Freeman House rebar shown in a transverse section.
The hot-rolled structure is pearlite plus ferrite, with approximately 0.2% carbon.
(2% nital etch @ 600x magnification)
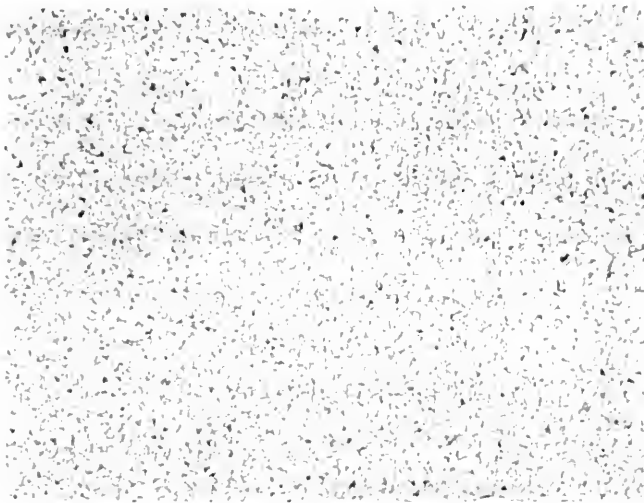
Figure 39
Optical micrograph of Freeman House rebar shown in a longitudinal section.
ASTM grain size is 10. (2% nital etch @ 100x magnification)

Figure 40
Optical micrograph of Freeman House rebar shown in a transverse section.
ASTM grain size is 10. (2% nital etch @ 100x magnification)

4.0   Proposed Assessment

Additional field investigation and laboratory analysis should be conducted to further evaluate the cause(s) of corrosion and the feasibility of protecting the reinforcing steel from further corrosion by electrochemical methods. Testing should include:

- Corrosion Potential Measurements
- Corrosion Rate Measurements
- Concrete Cover Measurements
- Electrical Continuity of Reinforcing Steel
- Chloride Ion Concentration Analysis
- Concrete Carbonation Depth Measurements
- Petrographic Analysis

4.1   Corrosion Potential Measurements

Corrosion potential measurements are a means of detecting corrosion activity affecting steel in concrete. These potentials are useful tools in determining the probability of corrosion activity on the structure at the time the measurements are taken. Potential readings would be taken in representative areas in accordance with ASTM C876. The corrosion potentials of steel in concrete are measured using a high impedance voltmeter in conjunction with a portable reference electrode, typically copper-copper sulfate (SCE). If the potentials are numerically less than -200 mV (CSE), there is a greater than 90% probability that no reinforcing steel corrosion is occurring at the time of the measurement. If the potentials range between -200 and -350 mV CSE, corrosion activity of the

reinforcing steel is uncertain and it is suspected that the high alkalinity of the concrete is beginning to break down. If the potentials are numerically greater than -350 mV CSE, there is a greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of the measurement. It should be noted that corrosion potential measurements are useful only in concrete structures affected by chloride induced corrosion.

4.2   Corrosion Rate Measurements

The instantaneous corrosion rate of a specific area of steel embedded in concrete can be determined using a polarization resistance measurement. The rate of corrosion is expressed in terms of weight loss of steel per unit area of steel per year. This method involves using a reference cell and a counter-electrode. A small amount of current is applied to a known area of reinforcing steel. The steel is allowed to polarize and the change in potential is recorded. The corrosion rate measurements provide an approximate time that concrete damage will occur as a result of corrosion activity.

4.3   Concrete Cover Measurements

Accurate information concerning the concrete cover over reinforcing steel is valuable in evaluating the corrosion control options for a particular structure. Depth of cover measurements are also important when used in conjunction with testing for chloride concentration and carbonation depth. Depth of reinforcing steel cover is measured using a

pachometer or rebar locator. This device uses a magnetic field to detect reinforcing steel in concrete and determine the depth of steel from the concrete surface.

4.4   Electrical Continuity of Reinforcing Steel

Adequate electrical continuity of reinforcing steel is a requirement for an effective cathodic protection system. Electrical continuity is also necessary for conducting valid corrosion potential surveys. Testing is accomplished by measuring the voltage drop between various locations in the reinforcing steel network. A voltmeter, reel of wire, and test leads are used for the evaluation. Voltage readings greater than 1.0 mV are usually indicative of electrical discontinuity.

4.5   Chloride Ion Concentration Analysis

To measure chloride ion concentrations in the concrete, concrete powder is collected at various depths on the structure. A standard method of determining the chloride content in a powder sample employs a laboratory chemical analysis (AASHTO T260). Chloride ion concentration profiles, based on the chemical analysis, can provide the degree of chloride contamination at the steel depth in the concrete. If the chloride concentrations at the steel depth have not reached the threshold limit, the projected time at which corrosion will occur can be determined.

4.6   Concrete Carbonation Depth Measurements

The depth of carbonation can be determined by the application of phenolphthalein to powdered concrete core samples. It is believed that the outer wythe of the Freeman House textile blocks is fully carbonated. The inner wythe, although more sheltered than the outer wythe, is potentially carbonated as well. These conditions should be confirmed by taking a series of small core samples throughout the structure.

4.7   Petrographic Analysis

Additional petrographic analysis should be used to determine the quality of the concrete in all areas of the Freeman House. Analysis by personnel trained in the assessment of concrete petrographic thin-sections would yield significant information including the water/cement ratio, characteristics of consolidation, uniformity, segregation, and finishing. Air content and parameters of the air void system can be estimated numerically, in terms of size and distribution of pores.

Petrographic examination can also be used to determine the condition of the concrete curing and degree of hydration. It can be used to detect possible freezing or premature setting of plastic concrete. In an older structure, petrography can determine causes of concrete distress such as elevated temperatures and freeze-thaw damage (not an issue in southern California), deleterious chemical reaction between the paste and the aggregates, sulfate attack, galvanic action and others.

5.0   Proposed Conservation Treatment

Several investigators have conducted on-site and laboratory analysis of the conditions at the Freeman House and have provided their recommendations for structural and seismic stabilization, repair and replacement of failed concrete, and other essential aspects of the overall preservation plan. It is crucial to the success of that plan, however, that corrosion of the reinforcing rod be addressed.

As one of the prime causes of material failure at the Freeman House, corrosion of the reinforcing rod must be minimized or the structure will continue to deteriorate. Simply repairing failed concrete will not be sufficient. Any preservation strategy should be implemented according to the Secretary of the Interior's Standards for Rehabilitation and Repair, and the American Institute for Conservation's Code of Ethics and Guidelines for Practice.

It is suggested that a three-phased approach be undertaken. The applicability of the electrochemical techniques reviewed above to the conditions found at the Freeman House can only be determined after conducting a thorough on-site assessment (Phase I) as outlined in the previous chapter. Such an assessment would determine which method would mitigate the ongoing corrosion of the reinforcing rod and, thereby reduce subsequent loss of the remaining textile blocks.

Phase II would be an on-site test to determine the efficacy of the most promising electrochemical method. Two or three small, but representative areas of the structure would be selected for the trial tests. The test-sites would be instrumented and the

corrosion potential monitored. The effectiveness of the treatment can be determined within a few days.

It is anticipated that the concrete of the outer wythe is fully carbonated due to its high porosity and direct exposure to the environment. It is also possible, due to the proximity to the ocean, that chloride levels may be unacceptably high. These factors would suggest that realkalization or chloride extraction, respectively, might be the appropriate technique. If it can be determined, however, that a cathodic protection system can be implemented then carbonated concrete and/or high chloride levels may be negated. With cathodic protection, the hydroxide ions produced at the surface of the steel reinforcement will cause the concrete to revert back to an alkaline state and chloride ions will slowly migrate away from the steel and toward the anode. Phase II testing of the selected technique should be required prior to receiving approval to move on to full implementation in Phase III.

Electrochemical mitigation of reinforcement corrosion, while preventing continued deterioration, will not restore the reinforcement to its original strength or condition. Deteriorated reinforcing rod can be replaced to enhance the structural stability of the building. The use of stainless steel or epoxy-coated reinforcing rod as a replacement material will, however, make electrochemical repair techniques unnecessary.

If replacement of reinforcing rod is undertaken, larger rod (e.g. ½") should be used to replace damaged vertical rods for improved bending characteristics. To obtain the full benefit of a larger vertical bar, it should be placed near (but, not touching) the extreme outside edge of the semicircular channel of the textile blocks. A flowable grout should be used to ensure complete encapsulation of the reinforcing rod.

Deteriorated concrete blocks will also need to be repaired or replaced. Repairs may include consolidation and patching. The effect of pre-consolidation of the concrete on the efficacy of the various electrochemical techniques has not been explored. Repairs to the concrete and electrochemical techniques would, ideally, be implemented at the same time to minimize disruption to the structure. It is possible, however, to introduce electrochemical remediation at any time.

The gap between the two wythes of concrete block was designed to provide an insulating air space.[45] Additional benefits can be gained if the air space is filled with a poured urethane foam or a lightweight insulating concrete. A urethane foam would be impermeable to water, provide a high insulation value, increase the rigidity of the walls, and provide a slight positive tension on the cross ties. An impermeable barrier may, however, trap moisture. This can be alleviated with the addition of well-placed drains.

[45]   Chusid, Jeffrey M. *Historic Structure Report: Samuel and Harriet Freeman House, Hollywood, California, Frank Lloyd Wright, 1924.* Los Angeles: University of Southern California (July 1989). p. 90.

6.0   Conclusion

Efforts to conserve reinforced concrete structures must include measures to re-pacify the steel, in addition to repairing the concrete. Several electrochemical methods of remedial concrete repair have been discussed. The methods considered include cathodic protection, realkalization, and chloride extraction.

Cathodic protection in concrete is achieved by applying small amounts of direct current to the reinforcing steel thereby causing the surface area of the steel in the affected area to become cathodic in relation to an externally positioned anode. Realkalization increases the pH of carbonated concrete by electro-osmosis, a process in which an externally applied electrolyte moves toward the reinforcing steel when subjected to an electric current. Chloride extraction is accomplished by placing an anode at the surface of the concrete and passing a direct current between the anode and the reinforcing steel, which serves as the cathode. Chloride ions will migrate toward the anode at the surface.

The potential application of electrochemical conservation techniques to the Samuel and Harriet Freeman House, a 1924 textile-block house designed by Frank Lloyd Wright, have been discussed. The construction methodology and present condition of the structure have been reviewed. Site-specific conditions suggest that electrochemical techniques are well-suited to the nearly continuous system of reinforcement. The concrete and the steel reinforcement have been partially characterized.

Further efforts should be undertaken in a three-phased approach. Phase I should include: 1) the measurement and mapping of corrosion potentials; 2) the determination of corrosion rates; 3) measurement of concrete cover; 4) confirmation of the electrical

continuity of the reinforcing rod; 5) a determination of chloride ion concentration in the concrete; 6) confirmation of carbonation depths; and 7) additional petrographic analysis of the concrete.

On-site testing in Phase II will confirm the viability of electrochemical remediation methods to the site-specific conditions found at the Freeman House. Due to the variability of the concrete, two or more tests should be performed. The electrochemical potential of the reinforcing steel should be monitored throughout the test to ensure that no further degradation is taking place. Samples of the concrete should be taken to confirm that the alkalinity of the concrete has been restored.

Electrochemical conservation techniques are well suited to historic and culturally significant reinforced concrete structures where replacement is not an option. When properly applied, cathodic protection, realkalization, and chloride extraction are minimally invasive. These methods restore the protective nature of concrete and prevent the further deterioration of reinforcing rod.

7.0   Bibliography

Freeman House and Textile Block Construction

Chusid, Jeffrey M. *A Guide to the Preservation of the Concrete Block Buildings of Frank Lloyd Wright: The Samuel Freeman House as A Case Study in Technical Research and Preservation Methodologies.* Los Angeles: University of Southern California (15 Nov. 1995).

Chusid, Jeffrey M. *Historic Structure Report: Samuel and Harriet Freeman House, Hollywood, California, Frank Lloyd Wright, 1924.* Los Angeles: University of Southern California (July 1989).

Gillespie, Ann. "Early Development of the Artistic Concrete Block: The Case of the Boyd Brothers." *Association for Preservation Technology Bulletin,* Volume XI, No. 2 (1979) p. 30-52.

Levine, Neil. *The Architecture of Frank Lloyd Wright.* Princeton: Princeton University Press (1996).

Nabih Youseff & Associates. *Freeman House, Hollywood, California: Architectural/Engineering Evaluation.* (14 Sept. 1995).

Sweeney, Robert L. *Wright in Hollywood: Visions of a New Architecture.* Cambridge, MA: The MIT Press (1994).

Wank Adams Slavin Associates. Test Program Proposal and Initial Site Visit Report: Samuel Freeman Residence (October 30, 1991).

Wank Adams Slavin Associates. 1992 Field Test Program for The Restoration of the Textile Block Facades: Samuel Freeman Residence (August 28, 1992).

Wright, Frank Lloyd. *An Autobiography.* London, New York, Toronto: Longmans, Green (1932).

History

Cowden, Adrienne Beaudet. *Historic Concrete: An Annotated Bibliography.* Washington, D.C.: National Park Service (1993).

Draffin, Jasper O. "A Brief History of Lime, Cement, Concrete and Reinforced Concrete." *Journal of the Western Society of Engineers,* Volume 48, No. 1 (March 1943) p. 14-47. Reprinted in *A Selection of Historic American Papers on Concrete 1876-*

1926, Howard Newlon, Jr., Editor. Publication SP-52. Detroit: American Concrete Institute, 1976. p. 5-38.

Huxtable, Ada Louise. "Concrete Technology in U.S.A.: Historical Survey." *Progressive Architecture*, Volume 41, No. 10 (Oct. 1960) p. 143-49.

Electrochemical Methods

American Concrete Institute. *Repair & Rehabilitation II*. Detroit, MI: American Concrete Institute (1993).

Anonymous. *Corrosion Damage to Concrete Structures in Western Asia*. Nairobi: United Nations Centre for Human Settlements (Habitat), 1990.

Bennett, Jack. "Corrosion of Reinforcing Steel in Concrete and its Prevention by Cathodic Protection." (undated) 13 pgs.

Bennett, Jack. "Electrochemical Treatment and Protection: Lessons Learned." *Pacific-Rim-2* (1995) p. 346-352.

Berger, Dean M. "Corrosion Theory." *ASM Metals Handbook, 9th Edition*, Volume 5: Surface Cleaning, Finishing, and Coating. Materials Park: ASM International (1982) p. 429-33.

Blackney, Keith and Bill Martin. "'Keyhole Surgery' Saves Cramps at Chiswick." *Construction Repair*. (Nov./Dec. 1995) p. 46-47.

Blackney, Keith and Bill Martin. "The Application of Cathodic Protection to Historic Buildings: Buried Metal Cramp Conservation in the Inigo Jones Gateway, Chiswick House Grounds, London." *Metals*, English Heritage Research Transactions. Volume 1 (April 1998) p. 83-94.

Broomfield, J.P. "Field Survey of Cathodic Protection on North American Bridges." *Corrosion* 31, No. 9 (Sept. 1992).

Brousseau, R., M. Arnott, and B. Baldock. "Laboratory Performance of Zinc Anodes for Impressed Current Cathodic Protection of Reinforced Concrete." *Corrosion* 51, No. 8 (August 1995) p. 639-644.

Chandler, Ian. *Repair & Renovation of Modern Buildings*. New York: McGraw-Hill (1991).

Chatterji, S. "Simultaneous Chloride Removal and Realkalization of Old Concrete Structures." *Cement and Concrete Research* 24, No. 6 (1994) p. 1051-4.

Collins, R.J. "Carbonation - Comparison of Results for Concretes Containing PFA, Cementitious Slag, or Alternative Aggregates." *Materials Science and Technology* 3 (Dec. 1987) p. 986-92.

Coney, William B. "Preservation of Historic Concrete: Problems and General Approaches." *Preservation Briefs 15*. Washington, D.C.: National Park Service, U.S. Department of the Interior, no date.

Corley, W. Gene. "Designing Corrosion Resistance into Reinforced Concrete." *Materials Performance* 34, No. 9 (September 1995) p. 54-58.

Davy, Sir Humphrey. "On the Corrosion of Copper Sheathing by Sea-Water, and On Methods of Preventing this Effect; and On Their Application to Ships of War and Other Ships." *Philosophical Transactions for 1824*. No. XVI, p. 273-280. Read before the Royal Society Jan. 22, 1824.

Davy, Sir Humphrey. "Additional Experiments and Observations on the Application of Electrical Combinations to the Preservation of the Copper Sheathing of Ships, and to Other Purposes." *Philosophical Transactions for 1824*. No. XVII, p. 281-5. Read before the Royal Society June 17, 1824.

Davy, Sir Humphrey. "Further Researches on the Preservation of Metals by Electro-Chemical Means." *Philosophical Transactions for 1825*. No. XVIII, p. 286-304. Read before the Royal Society June 9, 1825.

Haque, M.N. and M. Kawamura. "Carbonation and Chloride-Induced Corrosion of Reinforcement in Fly Ash Concretes." *ACI Materials Journal* (Jan.-Feb. 1992) p. 41-8.

Hover, Kenneth C. "Cathodic Protection for Reinforced Concrete Structures." *Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures*. Gajanan Sabnis, ed. Publication SP-85. Detroit: American Concrete Institute (1985) p. 175-208.

de Jonge, Wessel. "Concrete Repair and Material Authenticity: Electrochemical Preservation Techniques." *Association for Preservation Technology Bulletin*, Volume XXVIII, No. 4 (1997) p.51-57.

Kessler, Richard J., Rodney G. Powers, and Ivan R. Lasa. "Cathodic Protection Using Scrap and Recycled Materials." Paper No. 555, *Proceedings of Corrosion 91*. Houston: NACE International (1991).

Kessler, Richard J., Rodney G. Powers, and Ivan R. Lasa. "Zinc Mesh Anodes Cast into Concrete Pile Jackets." Paper No. 327, *Proceedings of Corrosion 96.* Houston: NACE International (1996).

Lankard, D.R., et. al. *Neutralization of Chloride in Concrete.* Battelle Columbus Laboratories, FHWA Report No. FHWA-RD-76-6 (September 1975).

Lasa, Ivan R., Rodney G. Powers, and Richard J. Kessler. "Practical Application of Cathodic Protection Systems for Reinforcing Steel Substructures in Marine Environment." *Repair and Rehabilitation of Reinforced Concrete Structures: The State of the Art.* Proceedings of the International Seminar, April 28-May 1, 1997, Marcaibo, Venezuela. Walter F. Silva-Araya, Oladis T. de Rincón, and Luis Pumarada O'Neill, editors. Reston, VA: American Society of Civil Engineers, 1998. p. 16-31.

Mailvaganam, Noel P., ed. *Repair and Protection of Concrete Structures.* Boca Raton: CRC Press (1992).

Makita, M., Y. Mori, and K. Katawaki. "Performance of Typical Protection Methods for Reinforced Concrete in Marine Environment." *Performance of Concrete in Marine Environment.* Publication SP-65. Detroit: American Concrete Institute (1980) p. 453-71.

Manning, G.D. and J. Ryell, *Durable Bridge Decks*, Ministry of Transportation and Communications, Ontario, Report RR203 (April 1976).

MacDonald, Susan. "Authenticity is More Than Skin Deep: Conserving Britain's Postwar Concrete Architecture." *Association for Preservation Technology Bulletin,* Volume XXVIII, No. 4 (1997) p.37-44.

McDonald, James E. and Willie E. McDonald. *Evaluation and Repair of Concrete Structures: Annotated Bibliography, 1978-1988.* Technical Report REMR-CS-36. U.S. Army Corps of Engineers. (June 1991).

Mietz., J. and B. Isecke. "Investigations on Electrochemical Realkalization for Carbonated Concrete." Paper No. 297, *Proceedings of Corrosion 94.* Houston: NACE International (1994).

Morrison, G.L., et. al. *Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis.* Kansas Department of Transportation, FHWA Report No. FHWA-KS-82-2 (August 1982).

Nagataki, S., M.A. Mansur, and H. Ohga. "Carbonation of Mortar in Relation to Ferrocement Construction." *ACI Materials Journal.* (Jan.-Feb. 1988) p. 17-25.

Nielson-Dharmaratne, Kurt and Frits O. Grønvold. "Internal Anodes in Concrete Structures." *Materials Performance* 31 (June 1992) p. 29-32.

Papadakis, Vagelis G., Michael N. Fardis, and Costas G. Vayenas. "Hydration and Carbonation of Pozzolanic Cements." *ACI Materials Journal* (Mar.-Apr. 1992) p. 119-30.

Papadakis, Vagelis G., Costas G. Vayenas, and Michael N. Fardis. "Fundamental Modeling and Experimental Investigation of Concrete Carbonation." *ACI Materials Journal* (Jul.-Aug. 1991) p. 363-73.

Papadakis, V.G., C.G. Vayenas, and M.N. Fardis. "Reaction Engineering Approach to the Problem of Concrete Carbonation." *AIChE Journal* 35, No. 10 (Oct. 1989) p. 1639-50.

Pedeferri, Pietro, Luca Bertolini, Fabio Bolzoni, and Tommaso Pastore. "Behavior of Stainless Steels in Concrete." *Repair and Rehabilitation of Reinforced Concrete Structures: The State of the Art.* Proceedings of the International Seminar, April 28-May 1, 1997, Marcaibo, Venezuela. Walter F. Silva-Araya, Oladis T. de Rincón, and Luis Pumarada O'Neill, editors. Reston, VA: American Society of Civil Engineers, 1998. p. 192-206.

Perenchio, William F. "Corrosion of Reinforcing Steel." 164-172. *Significance of Tests and Properties of Concrete and Concrete-Making Materials.* eds. Paul Klieger and Joseph F. Lamond. ASTM Publication No. STP 169C. Philadelphia: ASTM (1994).

Perkins, Philip H. *Repair, Protection, and Waterproofing of Concrete Structures.* New York: Elsevier (1986).

Polder, Rob B. and Peter C. Nuiten. "A Multi-Element Approach for Cathodic Protection of Reinforced Concrete." *Materials Performance* 33 (June 1994) p. 11-14.

Powers, Rodney G. and Ivan R. Lasa. *B.B. McCormick Bridge: Evaluation of Conductive Rubber, Perforated Zinc Sheet, and Titanium Mesh Cathodic Protection Systems.* Gainesville, FL: Florida Department of Transportation (December 1991).

de Rincón, Oladis, Matilde F. de Romero, Daniel Contreras, Oleyda Morón, Jesús Ludovic, José Bravo. "Electrochemical Diagnosis and Rehabilitation of Pilings for a Marine Bridge." *Materials Performance* 35, Vol. 35, No. 8 (August 1996) p. 14-21.

Schutt, William R. "Cathodic Protection of New High-Rise Buildings in Abu Dhabi." *Concrete International* (May 1992) p. 45-6.

Spellman, D.L. and R.F. Stratfull, "Chlorides and Bridge Deck Deterioration," *Highway Research Record*, No. 328, Transportation Research Board, Washington, DC (1970) p. 38-49.

Thangavel, K., N.S. Rengaswamy, and K. Balakrishnan. "Corrosion Resistance of Galvanized Steel in Concrete." *Materials Performance* 34, No. 9 (September 1995) p. 59-63.

Trethewey, Kenneth R. and John Chamberlain. *Corrosion for Students of Science and Engineering*. New York, John Wiley & Sons (1988).

Uhlig, Herbert H. and R. Winston Revie. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering*. New York: John Wiley & Sons (1985).

Wilson, J. Gilchrist. "Concrete." Chapter 2, *The Weathering and Performance of Building Materials*. John W. Simpson and Peter J. Horrobin, eds. New York: Wiley-Interscience (1970).

Analytical Techniques

American Society for Testing and Materials. Standard No. C 136-96a: Standard Method for Sieve Analysis of Fine and Coarse Aggregates. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 78-82.

American Society for Testing and Materials. Standard No. C 457-90: Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 225-37.

American Society for Testing and Materials. Standard No. C 641-82 (Reapproved 1991): Standard Test Method for Staining Materials in Lightweight Concrete Aggregates. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 303-07.

American Society for Testing and Materials. Standard No. C642-97: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 308-9.

American Society for Testing and Materials. Standard No. C 856-95: Petrographic Examination of Hardened Concrete. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 406-20.

American Society for Testing and Materials. Standard No. C876-91: Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 426-31.

American Society for Testing and Materials. Standard No. C1084-87: Portland-Cement Content of Hardened Hydraulic-Cement Concrete. Volume 04.02: Concrete and Aggregates. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1997) p. 557-62.

American Society for Testing and Materials. Standard No. E112-85: Standard Methods for Determining the Average Grain Size. Volume 03.03: Metallography; Nondestructive Testing. *Annual Book of ASTM Standards*. Philadelphia: ASTM (1986) p. 115-148.

DeHayes, Sharon M. and David Stark, Eds. *Petrography of Cementitious Materials*. ASTM Special Tech. Pub. No. 1215. Philadelphia: ASTM (1994).

Erlin, Bernard and David Stark, Eds. *Petrography Applied to Concrete and Concrete Aggregates*. ASTM Special Tech. Pub. No 1061. Philadelphia: ASTM (1990).

Ludirdja, Darmawan, Richard L. Berger, and J. Francis Young. "Simple Method for Measuring Water Permeability of Concrete." *ACI Materials Journal* 86, No. 5 (Sept./Oct. 1989) p. 433

McCrone, Walter C. and John Gustav Delly. *The Particle Atlas, 2nd Edition. Volume II: The Light Microscopy Atlas*. Ann Arbor: Ann Arbor Science Pub. (1973).

McCrone, Walter C. and John Gustav Delly. *The Particle Atlas, 2nd Edition. Volume III: The Electron Microscopy Atlas*. Ann Arbor: Ann Arbor Science Pub. (1973).

Teutonico, Jeanne Marie. "Measurement: pH," Experiment No. 7, *A Laboratory Manual for Architectural Conservators*. Rome: ICCROM (1988) p. 30-2.

Teutonico, Jeanne Marie. "Qualitative Analysis of Water-Soluble Salts and Carbonates," Experiment No. 16, *A Laboratory Manual for Architectural Conservators*. Rome: ICCROM (1988) p. 58-67.

Index

A

aluminum 1100, 3
aluminum 2017, 3
anode, 2, 5, 7, 13-16, 19, 20, 22, 23, 25, 26, 64, 66

B

B.B. McCormick bridge, 25
Boyle, Richard 9
brass, 3
bronze, 4
Burlington Skyway, 24

C

cadmium, 3
calcium carbonate, 11, 44, 45
calcium hydroxide, 11, 12, 22, 23, 44
carbon dioxide, 11, 12, 14, 15, 44
carbonation, 7, 11, 44, 59, 62, 70-73
cast iron, 3
catalyzed titanium mesh, 22
cathode, 2, 5, 13, 20, 67
cathodic protection, 1, 3, 4, 5, 6, 7, 8, 9, 21, 61, 64, 66, 68
cellulose fiber, 15, 16, 20, 23
Chiswick House, 9, 10
chloride extraction, 1, 21, 23, 64, 66, 68
chromium-iron, 3, 4
chromium-nickel-iron, 3, 4
concrete cover, 7, 60, 67
copper, 3, 4, 7, 54, 71
corrosion, 1, 2, 4, 5, 7, 8, 11, 14, 18, 19, 24, 25, 39, 59-64, 67
corrosion fatigue, 4

D

Davy, Humphrey 7
Duralumin, 4

E

electrolyte, 2, 3, 7, 8, 11, 13-16, 20, 22, 23, 24, 25, 26, 66
English Heritage, 9, 18, 70

F

Freeman House, 1, 27-31, 33, 34, 36-39, 43, 45, 47-54, 56-58, 62, 63, 65, 67-69

G

galvanic series, 3, 5
gold, 4
graphite, 4

H

Hastelloy C, 3, 4
Hoover Factory Building, 18

I

impressed current, 5, 6, 7, 9
Inconel, 3, 4
Inigo Jones Gatehouse, 9
intergranular corrosion, 4

L

Lankard, D.R., 24
lead, 3
lead-tin solders, 3
lithium borate, 22, 23, 26

M

magnesium, 3
MAKERS Industrial Ltd, 19
mathematical models, 6
Miller, John 12
monel, 4
Morrison, G.L. 24

N

nickel, 3, 4, 54
Norcure®, 12
Norwegian Concrete Technologies, 24

O

Opdal, Jacob 18

P

petrographic analysis, 26, 43
pH, 1, 6, 14, 15, 17, 19-21, 24, 44, 66
phenolphthalein, 17, 44
platinum, 4
Portland cement, 11, 44, 47, 48

R

S

T

V

Z